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WESTINGHOUSE ELECTRIC CORPORATION

AEROSPACE ELECTRICAL DIVISION

LIMA, OHIO

D-Spec. No. D 709553

SPACE ELECTRIC POWER SYSTEMS STUDY

FINAL REPORT
Volume 4

CONTRACT NAS5-1234

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FINAL REPORT
Volume 4

NOVEMBER 1961 THROUGH DECEMBER 1962

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ABSTRACT

Volume 1

This volume describes the general system arrangement and defines those system components necessary to efficiently (weight and power losses) supply a variable voltage d-c load at constant power. The system arrangement from turbine shaft to d-c bus includes: a generator; an exciter-regulator, for generator excitation control; a transformer; a rectifier, and switch gear. The switch gear includes circuit breakers, tap changers and bank switches as needed.

The components and materials for each system component were selected on the basis of temperature, frequency, power rating and availability. In most cases, the generator magnetic materials are Hiperco 27 for stator and SAE 4340 for rotor. The conductors are copper insulated with an inorganic material. Transformer materials include silicon-iron for core; copper conductors; and insulation of mica, glass and asbestos. Silicon semiconductor devices were chosen in all cases because of weight and power ratings.

The general approach to cooling each system component is discussed along with the mathematical development of the approach chosen. All components are cooled with a liquid coolant. The coolants used were potassium for the generator, NaK or potassium for high temperature power conditioning equipment, and MIPB for low temperature power conditioning equipment.

A method of determining size, weight and impedance of transmission lines is developed. The approach was to develop equations for the resistance of hollow and solid conductors, then balance the conductor power losses (I^2R) to the amount of power that can be radiated from the surface of the conductor.

Volume 2

This volume provides all the parametric data developed for each system component of the one-to-ten megawatt study. Generator ratings of one, two, five, and ten megawatts at speeds from 10 to 24 thousand rpm and coolant temperatures between 500F and 1100F are considered. All generator designs are limited by the allowable stress of the rotor material for a combination of speed and temperature. The combination usually decreases as the rating increases. Because of these limitations, the specific weight generally increases with rating. Additional designs at lower speeds, below 10,000 rpm, were added to the study because NASA indicated that turbine speeds might have to be decreased. Designs at one, two, and five megawatts are included.

The effect of advanced materials on generator weight and losses are also examined. The effect of better magnetic and insulation materials caused weight reductions of about 25 percent and efficiency improvements of about 0.5 percent.

The one-, five- and ten-megawatt transformer designs with maximum temperatures of 500F, 1000F, and 1500F show that except for some limitations the electro-magnetic weight is practically independent of rating for equal operating conditions and efficiency. The designs also show that aluminum conductors offer no weight or efficiency advantage over copper conductors.

The parametric data for the exciter-regulator and the rectifier show that the silicon semiconductors are the best choice from a weight standpoint. The data also shows that high-temperature devices do not offer any weight or efficiency advantage because their ratings are too low for this application.

Parametric data for circuit breakers, tap changers, and bank switches are included to evaluate the effect of step changes in direct voltage.

Volume 3

This volume provides three conceptual system designs based upon three missions. All designs are for one-megawatt ratings. The first design is based on a variable output voltage of 600 to 6000 volts. The second design is for a 4000-volt system and the third is for a 20,000-volt system. The specific weights of the first and third system are about equal while system number 2 has the lowest specific weight. The second system is lighter because no transformer is required. See Section VII for a tabular summary of each of the systems.

Volume 4

This volume provides all the parametric data and one preliminary system design for the extended portion of this contract. The ratings of the parametric data are 250 and 500 kw at 5000 volts.

As shown by the preliminary design summary, the specific weight of this system is higher than the specific weight of the one-megawatt system. The primary reason for the increase is this system supplies auxiliary a-c loads, the generator operates at a lower frequency, and the general concept of weight savings as system ratings increase is borne out for this type of system in ratings below about one megawatt.

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The objective of the study is to provide data for power systems whose ratings are less than one megawatt. This program is an extension of the one-to-ten megawatt study under NASA Contract NAS5-1234. The assumptions, goals, and conditions imposed on this study are comparable with the one-to-ten megawatt study.

This task includes:

1. Develop parametric data for electric power systems so that a set of design constants may be chosen. The system parameters to be considered are:

   a. Rating of 250 kw and 500 kw

   b. Direct voltage level of 5000 volts

   c. Generator rotor speed shall be 15,000, 20,000 and 30,000 rpm

   d. Alternating voltage of 1000, 1500, and 2140 volts

   e. Coolant temperatures between 500F and 800F

   f. Generator frequencies of 400, 1000 and 2000 cps

2. Provide one preliminary system design, chosen by the contractor, based upon the parametric data of 1, above.

A. PARAMETER SELECTION

1. Generator Types, Materials, and Cooling

The sections of Volume 1 and Volume 2 of this study entitled Comparison of Generator Types, Generator Materials, and Generator Cooling, are generally applicable to this study.

2. Choice of Generator Parameters

Following is a summary of the generator parameters used in this study:

Ratings: 300 and 600 kilowatts

Speeds: 8000, 12,000, and 24,000 rpm for 400-cps design
15,000, 20,000 and 30,000 rpm for 1000-cps and 2000-cps designs

Average Coolant Temperatures: 500F, 800F

Frequencies: 400, 1000, and 2000 cps

Current Densities: A-C Winding; 8500 to 9500 amp/in.^{2}
D-C Winding; 3500 to 4500 amp/in.^{2}

Flux Densities: Varied with temperature

Single Air Gap: .125 inch

Direct Axis Synchronous Reactance X_d: 1.2 p.u. ± 10%

Cell Thickness: See Section II of Volume 2.

Voltages (L-N): 1000, 1500, 2140 volts

B. 300-KILOWATT DESIGN SUMMARY

A summary of the most advantageous 300-kw generator designs in order of increasing weight and decreasing efficiency is as follows:

Design No.	Design	Electrical Weight	Design No.	Design	% Efficiency
43	2000 cps, 1000 V, 20000 rpm, 500F	192	1	400 cps, 1000 V 8000 rpm, 500F	94.2
44	2000 cps, 1500 V 20000 rpm, 500F	202	3	400 cps, 2140 V 8000 rpm, 500F	94.0
45	2000 cps, 2140 V 20000 rpm, 500F	204	25	1000 cps, 1000 V 20000 rpm, 500F	93.9
37	2000 cps, 1000 V 15000 rpm, 500F	236	19	1000 cps, 1000 V 15000 rpm, 500F	93.8
38	2000 cps, 1500 V 15000 rpm, 500F	237	2	400 cps, 1500 V 8000 rpm, 500F	93.7
41	2000 cps, 1500 V 15000 rpm, 800F	245	43	2000 cps, 1000 V 20000 rpm, 500F	93.5
40	2000 cps, 1000 V 15000 rpm, 800F	250	20	1000 cps, 1500 V 15000 rpm, 500F	93.5
25	1000 cps, 1000 V 20000 rpm, 500F	262	7	400 cps, 1000 V 12000 rpm, 500F	93.5
39	2000 cps, 2140 V 15000 rpm, 500F	262	26	1000 cps, 1500 V 20000 rpm, 500F	93.3
26	1000 cps, 1500 V 20000 rpm, 500F	264	8	400 cps, 1500 V 12000 rpm, 500F	93.2
42	2000 cps, 2140 V 15000 rpm, 800F	274	44	2000 cps, 1500 V 20000 rpm, 500F	93.1
19	1000 cps, 1000 V 15000 rpm, 500F	280	45	2000 cps, 2140 V 20000 rpm, 500F	93.1

Combining like design points from the preceding tabulation, the 300-kw designs having lowest weight and highest efficiency are:

Design No.	Freq. (cps)	Rating Voltage (volts)	Rating Speed (rpm)	Coolant Temp.	Electro-Magnetic Weight	Efficiency
43	2000	1000	20000	500F	192 lbs.	93.5%
44	2000	1500	20000	500F	202 lbs.	93.1%
45	2000	2140	20000	500F	204 lbs.	93.1%
25	1000	1000	20000	500F	262 lbs.	93.9%
26	1000	1500	20000	500F	264 lbs.	93.3%
19	1000	1000	15000	500F	280 lbs.	93.8%

C. 600-KILOWATT DESIGN SUMMARY

A summary of the most advantageous 600-kw generator designs in order of increasing weight and decreasing efficiency is as follows:

Design No.	Design	Electrical Weight
97	2000 cps, 1000 V 20000 rpm, 500F	342
98	2000 cps, 1500V 20000 rpm, 500F	357
99	2000 cps, 2140 V 20000 rpm, 500F	370
91	2000 cps, 1000 V 15000 rpm, 500F	410
93	2000 cps, 2140 V 15000 rpm, 500F	427
92	2000 cps, 1500V 15000 rpm, 500F	437
80	1000 cps, 1500 V 20000 rpm, 500F	456
73	1000 cps, 1000 V 15000 rpm, 500F	484
74	1000 cps, 1500 V 15000 rpm, 500F	493
79	1000 cps, 1000 V 20000 rpm, 500F	505
75	1000 cps, 2140 V 15000 rpm, 500F	507
81	1000 cps, 2140 V 20000 rpm, 500F	516

Design No.	Design	% Efficiency
73	1000 cps, 1000 V 15000 rpm, 500F	95.4
57	400 cps, 2140 V 8000 rpm, 500F	95.2
74	1000 cps, 1500 V 15000 rpm, 500F	95.1
56	400 cps, 1500 V 8000 rpm, 500F	95.0
80	1000 cps, 1500 V 20000 rpm, 500F	94.8
79	1000 cps, 1000 V 20000 rpm, 500F	94.7
81	1000 cps, 2140 V 20000 rpm, 500F	94.6
55	400 cps, 1000 V 8000 rpm, 500F	94.6
75	1000 cps, 2140 V 15000 rpm, 500F	94.5
60	400 cps, 2140 V 8000 rpm, 800F	94.4
97	2000 cps, 1000 V 20000 rpm, 500F	94.2
98	2000 cps, 1500 V 20000 rpm, 500F	94.2

Combining like design points from the preceding tabulation the 600-kw designs having lowest weight and highest efficiency are:

Design Design No.	Freq. (cps)	Rating Voltage (volts)	Rating Speed (rpm)	Coolant Temp.	Electro-Magnetic Weight	Efficiency
97	2000	1000	20000	500F	342 lbs.	94.2%
98	2000	1500	20000	500F	357 lbs.	94.2%
80	1000	1500	20000	500F	456 lbs.	94.8%
73	1000	1000	15000	500F	484 lbs.	95.4%
74	1000	1500	15000	500F	493 lbs.	95.1%
79	1000	1000	20000	500F	505 lbs.	94.7%
75	1000	2140	15000	500F	507 lbs.	94.5%
81	1000	2140	20000	500F	516 lbs.	94.6%

D. TABULATED DATA

This section presents the detailed information of each generator design, in tabular form, used to generate the summary tables of Sections II-B and II-C. The data in each table are for the following generator designs:

Table No.	Rating (kw)	Frequency (cps)
1	300	400
2	300	1000
3	300	2000
4	600	400
5	600	1000
6	600	2000
7	1000	400
7	1000	1000

TABLE 1.

300-KW, INDUCTOR-ALTERNATOR DESIGNS AT 400 CPS

DESIGN NO.	RPM	AVG COOLANT TEMP (°F)	GEN VOLTS L-N	% EFFICIENCY η	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe = Iron, Cu = Copper, W = Windage: Fe	Cu	W	SINGLE STK LGTH (IN)	ROTOR O.D. (IN)	MAX GEN O.D. (IN)	TOTAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P.U. X_d	MAX. ALLOWABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
1	8000	500	1000	94.2	555	3.77	5.84	12.7	.005	3.74	13.5	20.8	14.0	197	1.18	63700	8063
2	8000	500	1500	93.7	565	3.76	6.21	14.1	.005	3.76	13.5	20.9	13.9	230	1.22	63700	8136
3	8000	500	2140	94.0	615	3.77	7.00	12.2	.006	3.87	13.8	21.5	14.2	197	1.16	63700	8438
4	8000	800	1000	92.8	559	5.05	5.00	18.3	.151	3.75	13.5	20.8	14.0	264	1.18	15000	8093
5	8000	800	1500	92.1	568	5.05	5.36	20.3	.154	3.78	13.6	20.9	13.9	310	1.23	15000	8172
6	8000	800	2140	92.7	618	5.06	6.03	17.6	.168	3.88	13.8	21.6	14.2	257	1.16	15000	8470
7	12000	500	1000	93.5	512	3.84	7.88	13.0	.013	3.38	12.9	19.7	14.5	342	1.31	63700	17749
8	12000	500	1500	93.2	580	3.87	8.89	13.0	.016	3.80	13.4	20.5	14.8	358	1.16	63700	18750
9	12000	500	2140	92.0	556	4.49	8.96	17.2	.015	3.62	13.2	20.3	14.2	487	1.23	63700	18474
10	12000	800	1000	90.8	623	5.22	9.97	19.6	.841	2.93	15.2	21.9	14.1	594	1.06	30000	22833
11	12000	800	1500	89.0	884	6.26	11.9	24.1	1.20	4.80	16.5	23.7	17.4	803	.96	30000	26362
12	12000	800	2140	88.9	685	6.46	9.21	27.3	.902	3.45	15.4	22.4	13.8	837	1.12	30000	23340
13	24000*	500	1000	81.8	752	13.8	28.8	38.0	.144	2.72	14.1	24.8	15.8	2087	.91	63700	87137**
14	24000*	500	1500	81.5	712	16.7	20.9	47.2	.112	4.18	13.4	21.3	19.5	4662	1.26	63700	80314**
15	24000*	500	2140	83.6	893	16.0	20.0	33.9	.118	5.67	13.5	21.4	20.9	3082	.99	63700	81370**
16	24000*	800	1000	No Practical Design Obtained													
17	24000*	800	1500	No Practical Design Obtained													
18	24000*	800	2140	No Practical Design Obtained													
				Extremely High AC Winding End Extension Temperatures Produced 0 Efficiency Designs at 400 CPS, 24000 RPM, 800°F Avg. Coolant Temperature.													

* 2 Pole Designs for Comparison Purposes Only
** Designs Exceeded Rotor Steel Stress Limits

TABLE 2.

300-KW, INDUCTOR-ALTERNATOR DESIGNS AT 1000 CPS

DE-SIGN NO.	RPM	AVG COOL-ANT TEMP (F°)	GEN VOLTS L-N	% EFFI-CIENCY	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK LGTH (IN)	RO-TOR O. D. (IN)	MAX GEN O. D. (IN)	TO-TAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P. U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
							Fe	Cu	W								
19	15000	500	1000	93. 8	280	3. 96	8. [illegible]3	11. 2	. 011	2. 26	10. 9	16. 9	11. 6	185	1. 24	63700	20916
20	15000	500	1500	93. 5	294	3. 57	9. 73	11. 2	. 013	2. 27	11. 3	17. 3	11. 6	204	1. 14	63700	22192
21	15000	500	2140	92. 4	303	4. 31	10. 4	14. 3	. 013	2. 33	11. 3	17. 5	12. 2	275	1. 20	63700	22222
22	15000	800	1000	92. 7	310	4. 66	7. 81	15. 3	. 588	2. 06	12. 3	17. 9	11. 4	252	1. 21	30000	24678
23	15000	800	1500	92. 0	319	5. 19	8. 25	17. 4	. 597	2. 04	12. 4	18. 1	11. 5	304	1. 22	30000	24837
24	15000	800	2140	90. 8	338	5. 66	9. 11	20. 7	. 649	2. 10	12. 6	18. 6	11. 7	390	1. 20	30000	25639
25	20000	500	1000	93. 9	262	3. 16	9. 96	9. 62	. 024	2. 24	10. 8	16. 4	11. 6	262	1. 12	63700	37328
26	20000	500	1500	93. 3	264	3. 68	10. 2	11. 5	. 024	2. 19	10. 7	16. 4	11. 6	264	1. 19	63700	37129
27	20000	500	2140	92. 8	287	4. 40	11. 4	11. 8	. 024	2. 17	10. 8	16. 9	12. 2	287	1. 22	63700	37620
28	20000	800	1000	92. 4	286	4. 40	8. 75	14. 8	1. 15	1. 92	11. 9	17. 2	11. 3	286	1. 15	30000	42161 *
29	20000	800	1500	91. 6	295	4. 53	9. 75	16. 5	1. 25	2. 00	12. 1	17. 5	11. 4	295	1. 18	30000	43869 *
30	20000	800	2140	91. 6	313	5. 07	10. 5	15. 9	1. 24	1. 95	12. 1	17. 8	11. 8	313	1. 18	30000	43711 *
31	30000	500	1000	93. 0	232	3. 69	11. 6	11. 0	. 058	1. 89	10. 1	15. 3	12. 0	385	1. 31	63700	81597 *
32	30000	500	1500	92. 8	245	3. 53	12. 5	10. 9	. 060	2. 04	10. 2	15. 6	11. 9	389	1. 22	63700	81915 *
33	30000	500	2140	91. 7	256	3. 70	13. 9	13. 1	. 066	2. 08	10. 4	15. 9	11. 9	499	1. 20	63700	85376 *
34	30000	800	1000	91. 1	276	4. 39	11. 9	14. 2	3. 16	1. 76	11. 6	16. 8	11. 8	530	1. 08	30000	93902 *
35	30000	800	1500	90. 5	282	4. 67	12. 4	15. 8	3. 27	1. 80	11. 6	17. 1	11. 6	591	1. 11	30000	95545 *
36	30000	800	2140	88. 9	281	5. 59	12. 9	21. 5	3. 22	1. 91	11. 6	17. 0	11. 8	593	1. 25	30000	95808 *

* Designs Exceeded Rotor Steel Stress Limit

TABLE 3.

300-KW, INDUCTOR-ALTERNATOR DESIGNS AT 2000 CPS

DE-SIGN NO.	RPM	AVG COOL-ANT TEMP (°F)	GEN VOLTS L-N	% EFFI-CIENCY	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage			SIN-GLE STK LGTH (IN)	RO-TOR O. D. (IN)	MAX GEN O. D. (IN)	TO-TAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P. U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
							Fe	Cu	W								
37	15000	500	1000	92.2	236	4.29	12.9	12.6	.012	1.74	11.1	16.4	10.1	184	1.23	63700	22466
38	15000	500	1500	92.3	237	3.36	12.1	12.4	.013	2.53	11.2	16.4	10.4	133	1.24	63700	23099
39	15000	500	2140	90.9	262	4.89	15.8	14.2	.012	2.32	11.0	17.0	11.0	207	1.19	63700	21375
40	15000	800	1000	92.7	250	3.95	9.92	13.3	.507	1.99	11.9	17.0	9.8	145	1.08	30000	23610
41	15000	800	1500	91.5	245	4.83	9.96	17.6	.468	2.23	11.7	16.8	10.0	177	1.31	30000	22845
42	15000	800	2140	90.4	274	5.90	12.4	18.9	.529	1.94	12.0	17.6	10.6	263	1.21	30000	23810
43	20000	500	1000	93.5	192	3.27	11.3	9.53	.018	1.99	10.2	15.1	10.1	139	1.26	63700	34936
44	20000	500	1500	93.1	202	3.31	12.5	9.87	.019	1.90	10.2	15.4	10.1	167	1.11	63700	34587
45	20000	500	2140	93.1	204	3.53	12.6	9.72	.021	2.35	10.5	15.6	10.3	133	1.23	63700	37314
46	20000	800	1000	92.4	216	4.13	10.3	13.5	.866	1.60	11.2	16.0	9.8	211	1.16	30000	38688 *
47	20000	800	1500	91.7	207	4.58	10.0	16.5	.790	1.80	11.0	15.7	10.0	220	1.82	30000	37266 *
48	20000	800	2140	90.8	246	4.72	12.7	16.8	.999	1.82	11.6	16.9	10.5	289	1.08	30000	40228 *
49	30000	500	1000	93.2	170	2.75	13.1	8.89	.051	2.03	9.9	14.4	10.5	167	1.22	63700	68978 *
50	30000	500	1500	92.1	170	4.28	13.3	12.5	.042	1.39	9.5	14.2	10.5	338	1.30	63700	73460 *
51	30000	500	2140	91.8	192	3.74	15.9	10.8	.050	1.80	9.8	15.0	10.8	275	1.07	63700	75886 *
52	30000	800	1000	91.8	191	3.36	12.6	11.9	2.51	1.75	11.0	15.3	10.4	240	1.16	30000	88970 *
53	30000	800	1500	91.9	187	3.93	11.6	12.8	2.21	1.61	10.7	15.2	10.1	276	1.22	30000	83492 *
54	30000	800	2140	89.7	205	5.92	13.3	18.9	2.18	1.49	10.7	15.6	10.8	456	1.26	30000	82857 *

* Designs Exceeded Rotor Steel Stress Limit

TABLE 4.

600-KW, INDUCTOR-ALTERNATOR DESIGNS AT 400 CPS

DE-SIGN NO.	RPM	AVG COOL-ANT TEMP (°F)	GEN VOLTS L-N	% EFFI-CIENCY	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage: Fe	Cu	W	SIN-GLE STK LGTH (IN)	RO-TOR O.D. (IN)	MAX GEN O.D. (IN)	TO-TAL GEN LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P.U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX ROTOR STRESS (psi)
55	8000	500	1000	94.6	1373	3.84	15.2	19.2	.017	7.29	17.4	26.4	21.6	295	1.28	63700	12566
56	8000	500	1500	95.0	1116	4.09	12.9	18.5	.013	5.52	16.4	25.6	17.2	266	1.25	63700	11198
57	8000	500	2140	95.2	1236	4.00	14.6	15.4	.014	5.84	16.8	26.5	17.6	214	1.18	63700	11727
58	8000	800	1000	93.5	1381	5.16	13.4	28.2	.506	7.30	17.5	26.4	21.6	398	1.28	15000	12610
59	8000	800	1500	94.0	1122	5.50	11.1	27.0	.381	5.54	16.4	25.7	17.2	361	1.26	15000	11237
60	8000	800	2140	94.4	1241	5.35	12.5	22.4	.429	5.85	16.9	26.5	17.6	285	1.18	15000	11763
61	12000	500	1000	91.9	1679	4.91	2.98	23.2	.065	8.13	18.1	26.9	26.3	799	1.18	63700	31347
62	12000	500	1500	92.8	1436	4.63	2.52	21.4	.055	6.93	17.5	26.5	22.3	648	1.23	63700	29431
63	12000	500	2140	92.9	1144	4.98	2.06	25.3	.039	5.47	16.2	25.1	17.8	675	1.30	63700	25537
64	12000	800	1000	87.6	1863	8.85	2.72	43.8	4.10	6.26	21.3	30.1	23.3	1700	1.06	15000	41557*
65	12000	800	1500	87.3	1591	8.35	4.08	42.1	4.15	4.23	21.3	30.1	17.0	1707	.89	15000	41644*
66	12000	800	2140	89.2	1382	8.40	2.23	48.2	2.33	5.17	18.9	27.4	17.9	1770	1.26	15000	33168*
67	24000	500	1000	No Practical Designs - Extremely High Temperatures in the Long End-Extensions Resulted in Zero Efficiency Designs. Designs Were Originally Calculated For Comparison Purposes Only, Since 2 Pole Inductor Alternators Are Not Mechanically Practical													
68	24000	500	1500														
69	24000	500	2140														
70	24000	800	1000														
71	24000	800	1500														
72	24000	800	2140														

*Designs Exceeded Rotor Steel Stress Limit

TABLE 5.

600-KW, INDUCTOR-ALTERNATOR DESIGNS AT 1000 CPS

DE-SIGN NO.	RPM	AVG. COOL-ANT TEMP (°F)	GEN VOLTS L-N	% EFFI-CIENCY	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe - Iron Cu = Copper W = Windage			SIN-GLE STK LGTH (IN)	RO-TOR O. D. (IN)	MAX GEN O. D. (IN)	TO-TAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P. U. X_d	MAX. ALLOW-ABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
							Fe	Cu	W								
73	15000	500	1000	95.4	484	3.16	16.6	12.4	.025	3.33	12.9	20.1	13.1	174	1.22	63700	26461
74	15000	500	1500	95.1	493	3.53	17.4	13.8	.025	3.39	13.0	20.2	14.2	202	1.24	63700	26658
75	15000	500	2140	94.5	507	3.81	18.5	16.7	.025	3.35	13.1	20.5	13.4	262	1.23	63700	27182
76	15000	800	1000	94.6	515	4.48	14.3	18.7	1.20	2.84	14.3	21.1	12.4	357	1.26	30000	31056 *
77	15000	800	1500	94.2	552	4.47	15.7	19.9	1.34	3.07	14.7	21.6	12.7	282	1.23	30000	32386 *
78	15000	800	2140	93.4	582	4.71	16.9	23.9	1.46	3.15	14.9	22.1	12.8	357	1.23	30000	33396 *
79	20000	500	1000	94.7	505	2.71	21.2	12.3	.064	4.18	13.2	20.0	16.1	222	1.30	63700	50665
80	20000	500	1500	94.8	456	3.32	19.4	13.7	.050	3.22	12.6	19.5	13.1	277	1.26	63700	45727
81	20000	500	2140	94.6	516	3.16	22.8	11.6	.058	3.46	13.0	20.3	13.4	237	1.12	63700	48116
82	20000	800	1000	92.9	583	3.72	22.4	20.0	3.64	3.81	15.2	21.6	15.1	400	1.31	30000	63469 *
83	20000	800	1500	93.6	518	4.33	18.5	20.1	2.74	2.91	14.3	20.9	12.7	402	1.22	30000	55884 *
84	20000	800	2140	93.6	567	4.34	20.9	17.1	2.99	3.09	14.6	21.6	13.9	337	1.14	30000	57647 *
85	30000	500	1000	92.3	598	2.93	37.1	13.1	.240	4.60	13.7	20.6	17.6	511	1.10	63700	125512 *
86	30000	500	1500	92.4	595	2.90	37.3	12.2	.231	4.59	1[illegible].6	20.5	17.0	441	1.09	63700	123797 *
87	30000	500	2140	93.1	452	3.75	27.6	16.7	.149	3.00	12.4	19.1	13.0	575	1.23	63700	105691 *
88	30000	800	1000	91.2	524	4.56	27.3	22.0	8.59	3.15	14.3	20.4	15.7	776	1.26	30000	130052 *
89	30000	800	1500	90.5	592	4.16	33.2	19.5	10.51	3.48	14.9	21.3	15.2	681	1.15	30000	140758 *
90	30000	800	2140	90.3	556	4.98	30.7	25.1	8.91	2.99	14.4	20.9	13.2	881	1.07	30000	130748 *

* Designs Exceeded Rotor Steel Stress Limit

TABLE 6.

600-KW, INDUCTOR-ALTERNATOR DESIGNS AT 2000 CPS

DESIGN NO.	RPM	AVG COOLANT TEMP (°F)	GEN VOLTS L-N	% EFFICIENCY	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage: Fe	Cu	W	SINGLE STK LGTH (IN)	ROTOR O.D. (IN)	MAX GEN O.D. (IN)	TOTAL GEN LGTH (IN)	APPROX AVG AC & FLD WDG TEMP. RISE (°F)	P.U. X_d	MAX ALLOWABLE ROTOR STRESS (psi)	ACTUAL MAX ROTOR STRESS (psi)
91	15000	500	1000	93.6	410	3.02	20.8	20.3	.025	3.92	12.9	19.2	12.6	133	1.28	63700	27151
92	15000	500	1500	94.1	437	2.62	23.1	14.4	.027	4.06	13.2	19.8	12.8	110	1.01	63700	28054
93	15000	500	2140	93.8	427	2.89	24.0	15.8	.026	3.68	13.0	19.7	12.3	139	1.13	63700	27310
94	15000	800	1000	93.2	443	3.47	21.1	21.2	1.28	3.09	14.5	20.5	11.5	170	1.11	30000	32835*
95	15000	800	1500	93.0	466	3.36	23.7	19.8	1.48	3.28	15.0	20.9	11.9	177	1.08	30000	35079*
96	15000	800	2140	93.7	454	3.86	19.9	19.1	1.18	3.27	14.3	20.6	11.6	161	1.14	30000	31149*
97	20000	500	1000	94.2	342	2.57	21.8	15.2	.048	3.10	12.5	18.3	11.8	158	1.32	63700	46704
98	20000	500	1500	94.2	357	2.55	23.5	13.8	.048	3.47	12.3	18.4	12.2	142	1.14	63700	45222
99	20000	500	2140	93.1	370	2.74	30.4	14.4	.056	3.30	12.9	18.8	12.3	184	1.18	63700	51914
100	20000	800	1000	93.7	372	3.34	20.2	18.3	2.15	2.92	13.6	19.2	11.6	186	1.30	30000	52914*
101	20000	800	1500	92.9	405	3.25	25.9	17.3	2.65	2.88	14.2	19.9	11.6	211	1.03	30000	57478*
102	20000	800	2140	93.8	379	3.55	21.0	16.9	2.00	2.74	13.4	19.3	11.2	204	1.14	30000	50420*
103	30000	500	1000	94.4	296	2.29	25.4	10.1	.105	2.94	11.5	17.2	11.9	160	1.18	63700	93584*
104	30000	500	1500	94.0	299	2.47	26.1	12.3	.107	2.94	11.6	17.3	10.8	205	1.19	63700	94318*
105	30000	500	2140	94.1	300	2.74	26.5	11.1	.100	2.79	11.4	17.3	11.6	207	1.22	63700	91411*
106	30000	800	1000	93.2	328	2.96	24.8	13.6	5.18	2.54	12.8	18.2	11.6	236	1.12	30000	107778*
107	30000	800	1500	92.8	337	3.07	25.5	15.5	5.56	2.78	13.0	18.4	11.9	263	1.20	30000	111672*
108	30000	800	2140	92.8	331	3.48	24.5	17.7	5.16	2.47	12.8	18.4	11.3	285	1.23	30000	108281*

*Designs Exceeded Rotor Steel Stress Limit

TABLE 7.

1-MEGAWATT, INDUCTOR-ALTERNATOR DESIGNS

DESIGN NO.	RPM	AVG. COOLANT TEMP (°F)	GEN VOLTS L-N	% EFFICIENCY	GEN WT (LBS)	FIELD PWR (KW)	LOSSES (KW) Fe = Iron Cu = Copper W = Windage: Fe	Cu	W	SINGLE STK LGTH (IN)	ROTOR O. D. (IN)	MAX GEN O. D. (IN)	TOTAL GEN. LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P. U. X_d	MAX. ALLOWABLE ROTOR STRESS (psi)	ACTUAL MAX. ROTOR STRESS (psi)
400 cps																	
109	12000	500	1000	90.4	2677	8.08	51.7	54.8	.124	9.3	20.8	30.4	28.5	1328	1.14	63700	39694
110	12000	500	1500	89.2	2902	8.36	60.1	60.6	.129	10.7	21.0	30.4	32.2	1368	1.27	63700	40453
111	12000	500	2140	90.7	2692	7.96	49.8	52.9	.123	9.3	20.8	30.5	26.6	1224	1.16	63700	39533
112	12000	800	1000	No Practical Designs Extremely High Temperature in Stator End Turn													
113	12000	800	1500	No Practical Designs Extremely High Temperature in Stator End Turn													
114	12000	800	2140	No Practical Designs Extremely High Temperature in Stator End Turn													
115	12000	500	1000	No Practical Design, 2 Pole Inductor Generators are not Mechanically Practical													
116	12000	500	1500	No Practical Design, 2 Pole Inductor Generators are not Mechanically Practical													
117	12000	500	2140	No Practical Design, 2 Pole Inductor Generators are not Mechanically Practical													
1000 cps																	
118	15000	500	1000	95.4	985	3.16	32.7	15.5	.070	6.5	16.1	24.4	18.9	164	1.22	63700	38454
119	15000	500	1500	95.2	855	3.18	32.7	17.4	.061	5.6	15.6	23.6	16.7	198	1.22	63700	36498
120	15000	500	2140	95.2	1044	3.18	32.7	14.2	.074	6.6	16.3	24.8	18.3	150	1.09	63700	38906
121	15000	800	1000	94.2	1065	3.98	35.2	21.8	4.13	5.2	18.6	26.3	16.7	271	1.10	30000	49852*
122	15000	800	1500	No Practical Design Obtained												30000	
123	15000	800	2140	No Practical Design Obtained												30000	
124	20000	500	1000	94.4	946	3.09	42.9	15.9	.136	6.5	15.6	23.6	19.9	265	1.29	63700	64749*
125	20000	500	1500	94.4	963	3.56	43.6	15.3	.136	6.1	15.9	24.2	18.0	274	1.04	63700	67317*
126	20000	500	2140	95.0	810	3.32	37.8	14.9	.117	5.3	15.1	23.0	16.3	234	1.30	63700	61401

* Designs Exceeded Rotor Steel Stress Limit

E. ANALYSIS OF PARAMETRIC DATA

1. Weight and Efficiency Versus Speed Curves (Figures 1 through 12)

All curves are at the end of section II-E.

The generator output voltage is proportional to the number of conductors in series and to the time rate of change of flux through the turns. For a given voltage, as both the speed and the frequency are increased, the required number of turns in series and/or the required flux per pole decreases, generally resulting in a decrease in generator weight. The 500F designs show a weight advantage over the 800F designs as explained in the following paragraphs. Maximum speeds, as limited by the strength of the rotor steel, were as follows:

a. At 500F, practical 300-and 600-kw designs were obtained for speeds up to 20,000 rpm.

b. At 800F, practical 300-kw designs were obtained for speeds up to 15,000 rpm.

c. At 800F, no practical 600-kw designs were obtained at speeds above 8000 rpm, since the rotor stress limit was exceeded at 12,000 rpm for the 400 cps designs and slightly exceeded at 15,000 rpm for the 1000 and 2000 cps designs.

At 8000 rpm, Hiperco-27 stator steel and SAE-4340 rotor steel were used for both 500F and 800F coolant temperatures. As shown on the curves in the generator materials section for Hiperco 27 (at 120 KL/in^2) and for SAE 4340 (at 85 KL/in^2), there is only a slight difference in magnetic characteristics between 600F and 900F, the assumed steel temperatures. At 8000 rpm, the slightly increased weight of the 800F generator, as shown in the tabulated data for Designs 4 through 6, is due principally to the higher IR drop in the windings which requires a higher internal generated voltage and thus a small increase in weight in order to produce the same full load terminal voltage as the 500F design.

At speeds of 12,000 rpm and above, it was necessary to use Westinghouse Nivco rotor steel for suitable strength at an average coolant temperature of 800F. The use of Nivco limited the rotor flux density to approximately 60 KL/in^2. This limitation required a larger rotor area and a corresponding increase in weight to carry the necessary flux.

All 24,000- and 30,000-rpm designs were found to exceed the stress limits of the rotor steel both at 500F and 800F. Because two-pole inductor alternators have been found impractical from a mechanical standpoint, the 400-

cps, 24,000-rpm designs were calculated for comparison purposes only.

At an average coolant temperature of 500F, 20,000 rpm was found to be the maximum speed practical for both 300- and 600-kw ratings without exceeding the stress limits of the rotor steel. At an average coolant temperature of 800F, 15,000 rpm was found to be the maximum speed practical for the 300-kw ratings, but this speed and temperature resulted in 600-kw designs which slightly exceeded the maximum allowable rotor-steel stress limits.

The 400-cps designs, in general, showed little advantage as the speed increased from 8000 rpm to 12,000 rpm. In only 3 cases was a weight advantage found at 12,000 rpm. In all cases the efficiency decreased as the speed was increased from 8000 rpm to 12,000 rpm. The disadvantage of the higher speed chiefly occurred for the 400-cps designs because of the length of the a-c stator-winding end extensions was significantly greater for the four-pole, 12,000-rpm designs than for the six-pole, 8000-rpm designs. The added copper length of the 12,000-rpm designs produced higher winding temperatures, higher copper (I^2R) losses, and added weight.

The 1000-cps and 2000-cps designs, in most cases, showed a weight and efficiency advantage at 20,000 rpm.

As shown by the curves, the 2000-cps designs had the lowest weights while the 400-cps designs had significantly higher weights.

In most cases the 1000-cps designs had higher efficiencies than the 2000-cps designs at 15,000-rpm while the efficiencies were, in general, not significantly different at 20,000 rpm.

Based upon the Weight and Efficiency Versus Speed Curves, the 500F, 2000-cps, 20,000-rpm designs have the least weight. The 1000-cps designs have slightly higher efficiencies at 20,000 rpm, but also have higher weights. The 500F, 2000-cps, 20,000-rpm designs thus appear to have the best combinations of low weight and high efficiency.

2. Weight and Efficiency Versus Voltage Curves (Figures 13 through 21)

As the rated voltage of a generator is increased either turns per phase or flux per pole must be increased. In addition, the required insulation thickness increases. Actual slot cell thicknesses used are given in the section on Generator Parameters (Section II of Volume 2). For a given power rating, as the rated voltage increases the rated current decreases, allowing a decrease in the conductor size.

The various voltage levels considered were found to have a relatively small effect on the generator weights in comparison to the effects obtained by varying frequency. In general, the per cent weight variations were similar for the various frequencies at the 1000, 1500, and 2140 line-to-neutral generator voltage levels considered.

For the majority of designs the weights increased as the rated voltage was increased. This indicated that the required insulation thicknesses, iron, and number of conductors had a more significant effect on the weight than did the decrease in copper size realized by the decreased current requirements.

The increased insulation thickness, in some cases, increased the average winding temperature thus increasing the a-c winding copper losses. In other cases, an increase in the number of conductors increased the a-c winding copper losses. Efficiencies were lowered for some of the designs by the increased copper and iron losses, which accompanied the increased voltage ratings. Other designs were found to have better combinations of parameters at the higher voltages, resulting in small improvements in efficiencies.

The following voltage levels were found, in general, to give the lowest weights and highest efficiencies for the various combinations of rating and frequency.

	Voltage for Lightest Wt.	Voltage for Highest Eff.
300 kw, 400 cps	1000 V	1000 V
300 kw, 1000 cps	1000 V	1000 V
300 kw, 2000 cps	1000, 1500 V	1000 V
600 kw, 400 cps	1500, 2140 V	2140 V
600 kw, 1000 cps	1000, 1500V	1000, 1500 V
600 kw, 2000 cps	1000 V	1000, 1500 V

Based on the above data 1000 volts appears to produce the best combinations of light-weight and high-efficiency for 300-kw ratings at 400, 1000, and 2000 cps. For 600-kw ratings: 2140 volts appears best for 400-cps; 1000- to 1500-volts appears best for 1000 cps; and 1000 volts appears best for 2000 cps.

3. Specific Weight and Efficiency Versus Rating Curves (Figures 22 through 33)

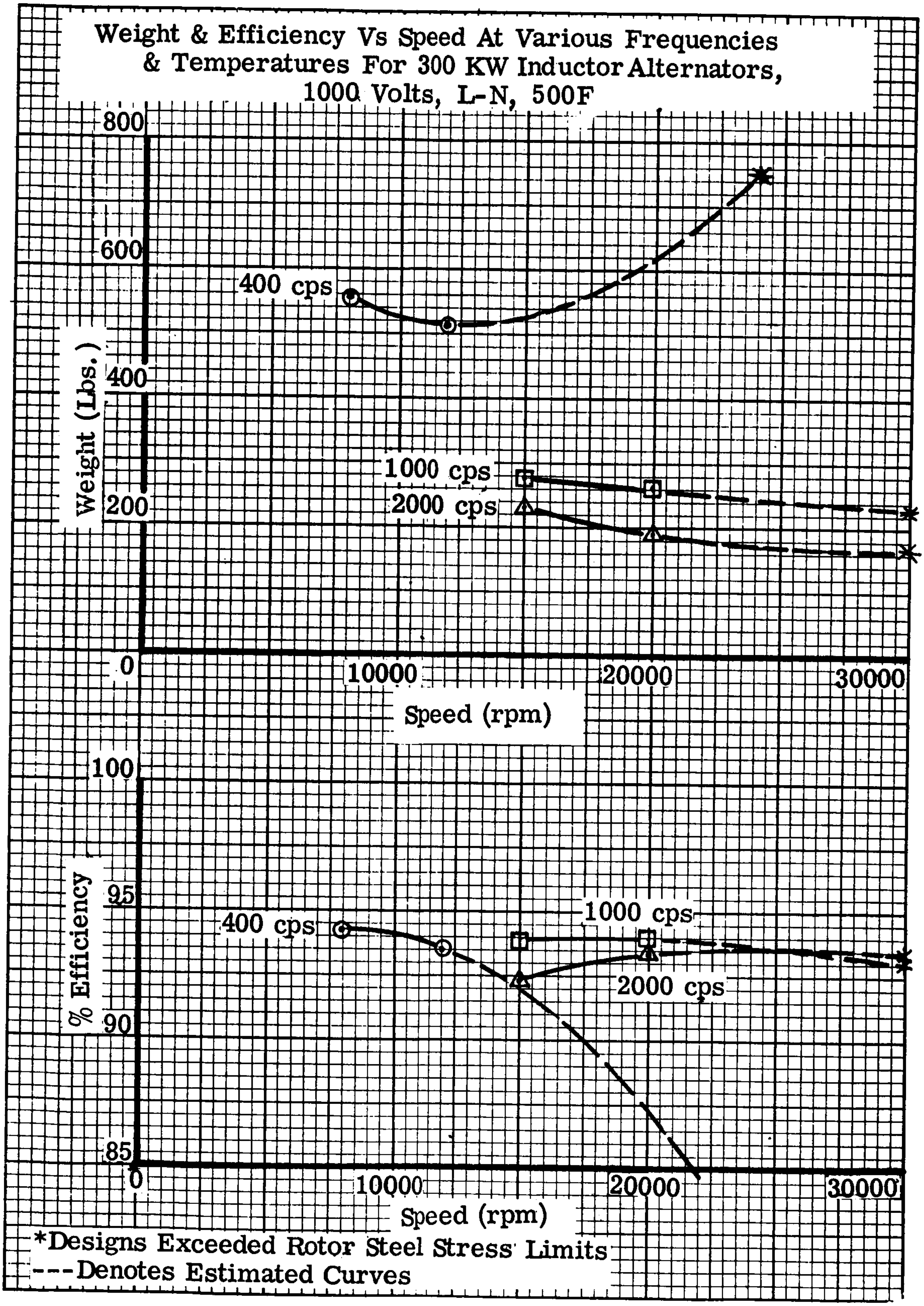
Since only 300-kw and 600-kw ratings were considered in this section of the program, the majority of these curves show only comparisons between the two ratings rather than general trends. Some available one-megawatt design points, from calculations made in other programs, are shown to aid in illustrating the effects of various ratings. The effects of varying frequency, speed, temperature, and voltage were discussed in previous sections.

At 1000 volts and 400 cps, both specific weight and efficiency are higher at 600 kw for the practical designs. The higher specific weights appear more significant than the increased efficiencies of the 600-kw, 1000-volt, 400-cps designs. At 1500 and 2140 volts and 400 cps, the efficiency advantages of the 600-kw designs appear to offset the slight increases in specific weight which occurred in some cases.

The 1000-cps and 2000-cps designs, in general, show both weight and efficiency advantages for the 600-kw ratings. The higher rating limited the number of practical 800F designs which did not exceed the rotor steel stress limits. The available one-megawatt design points show slightly higher specific weight and approximately equal efficiencies when compared to the 600-kw designs.

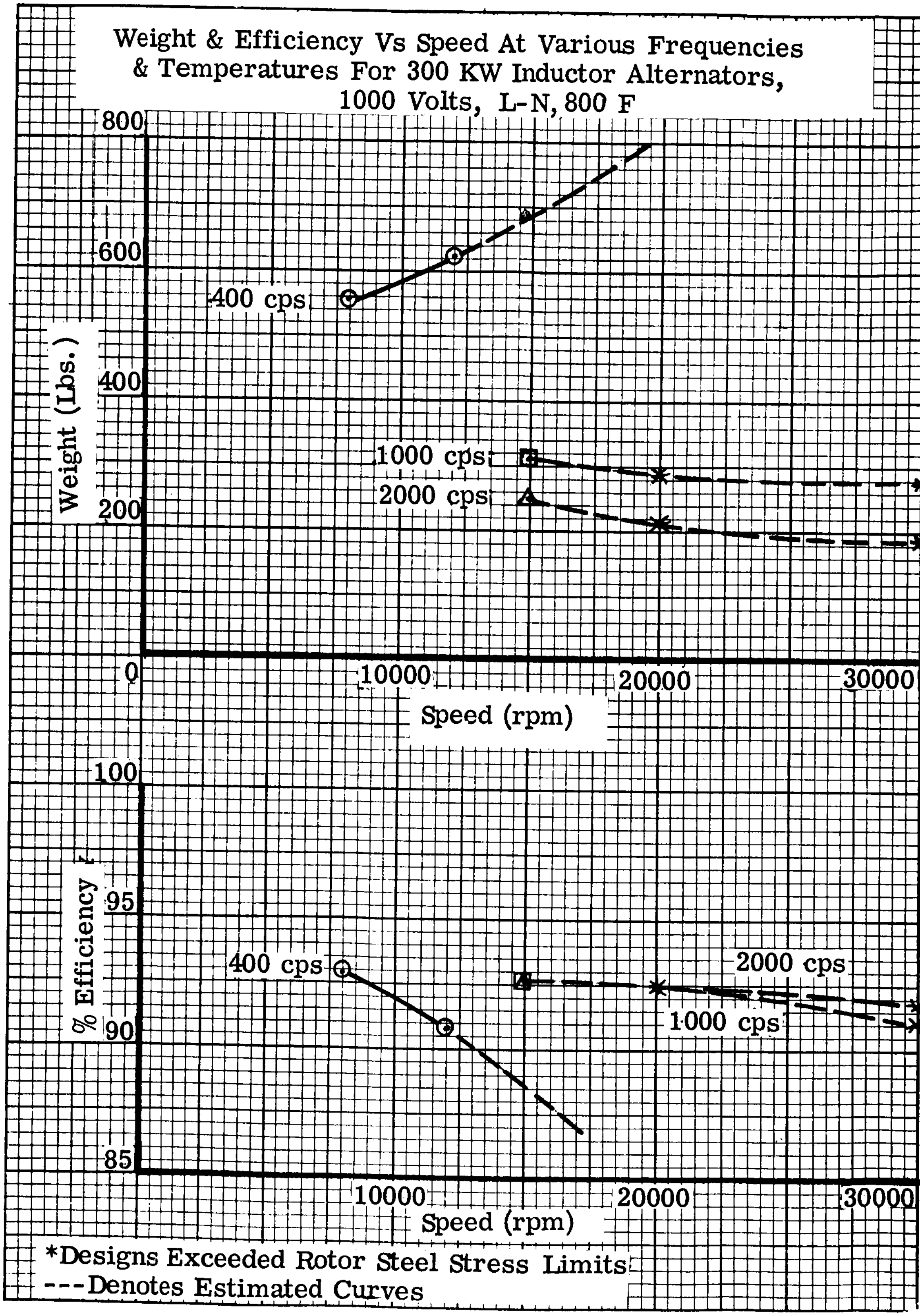
Based upon the designs calculated, for a specific combination of frequency and voltage, the following ratings appear most advantageous in terms of specific weight and efficiency.

400 cps, 1000 V - 300 kw
400 cps, 1500 and 2140 V - 600 kw
1000 cps, 1000, 1500, 2140 V - 600 kw
2000 cps, 1000, 1500, 2140 V - 600 kw



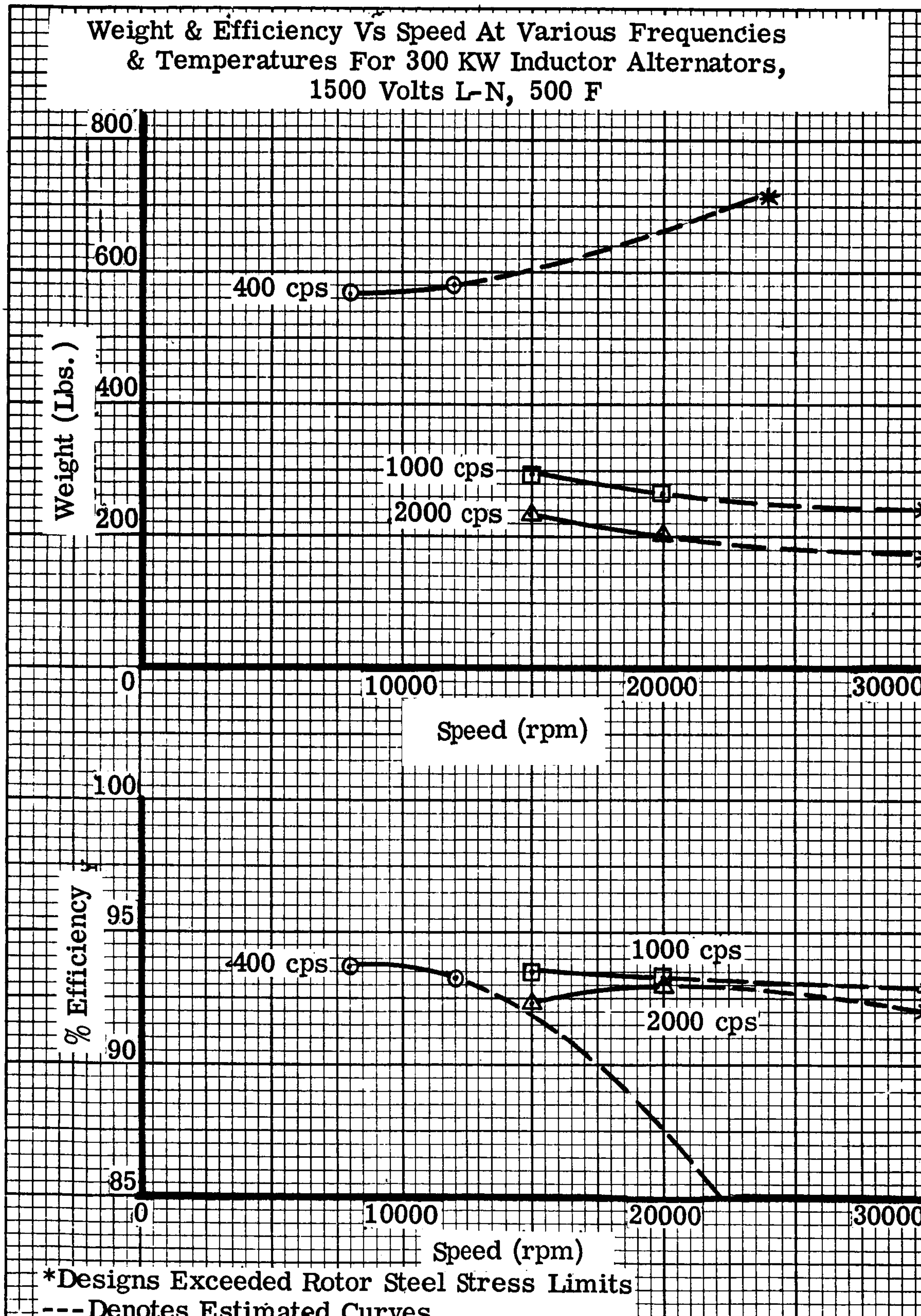
Weight & Efficiency Vs Speed At Various Frequencies & Temperatures For 300 KW Inductor Alternators, 1000 Volts, L-N, 500F
Weight (Lbs.)
800
600
400
200
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
% Efficiency
100
95
90
85
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 1.



Weight & Efficiency Vs Speed At Various Frequencies & Temperatures For 300 KW Inductor Alternators, 1000 Volts, L-N, 800 F
Weight (Lbs.)
800
600
400
200
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
% Efficiency
100
95
90
85
400 cps
2000 cps
1000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 2.



Weight & Efficiency Vs Speed At Various Frequencies & Temperatures For 300 KW Inductor Alternators, 1500 Volts L-N, 500 F
800
600
400
200
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
0
% Efficiency
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 3.

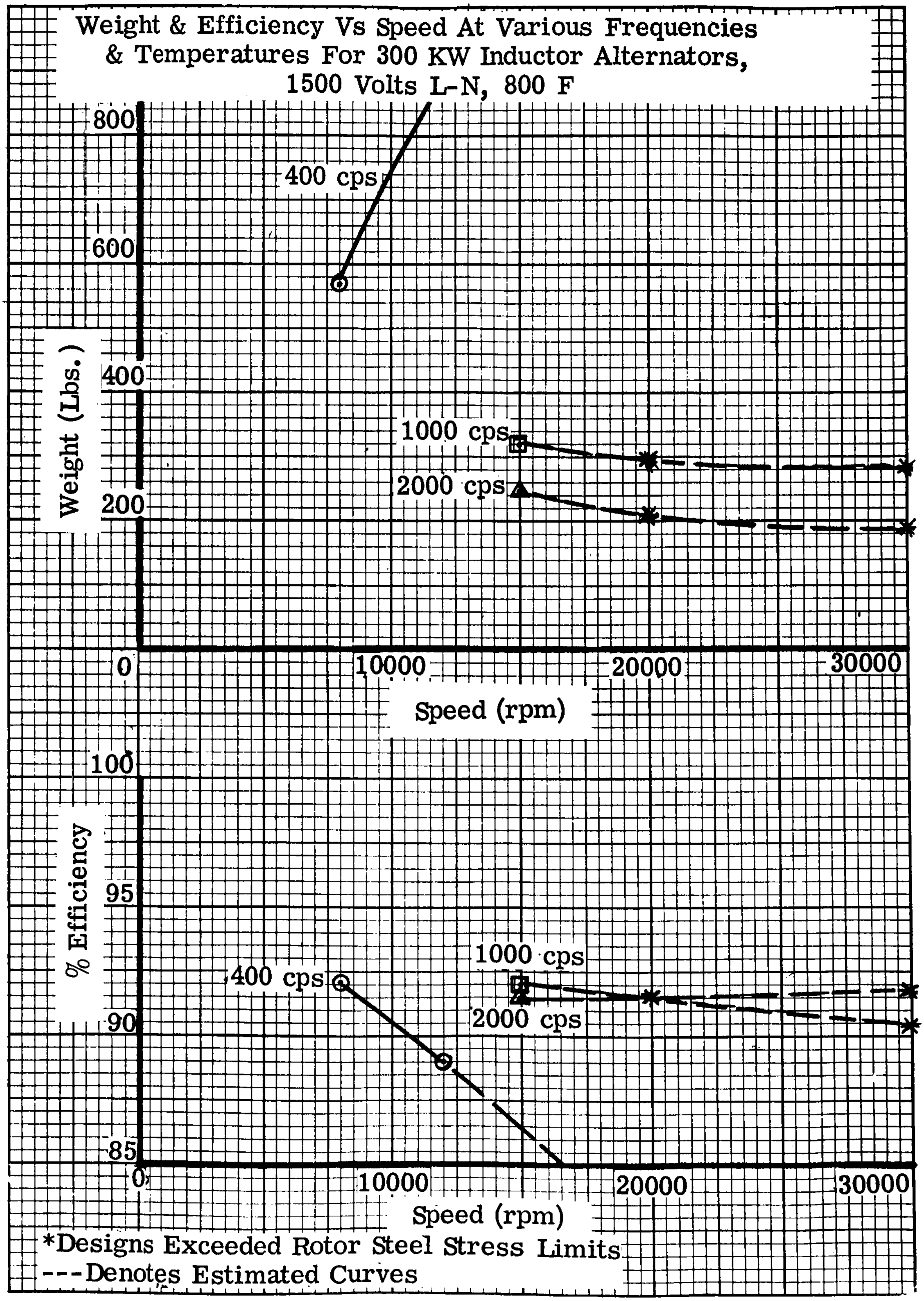

Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 300 KW Inductor Alternators,
1500 Volts L-N, 800 F
800
600
400
200
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
0
% Efficiency
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 4.

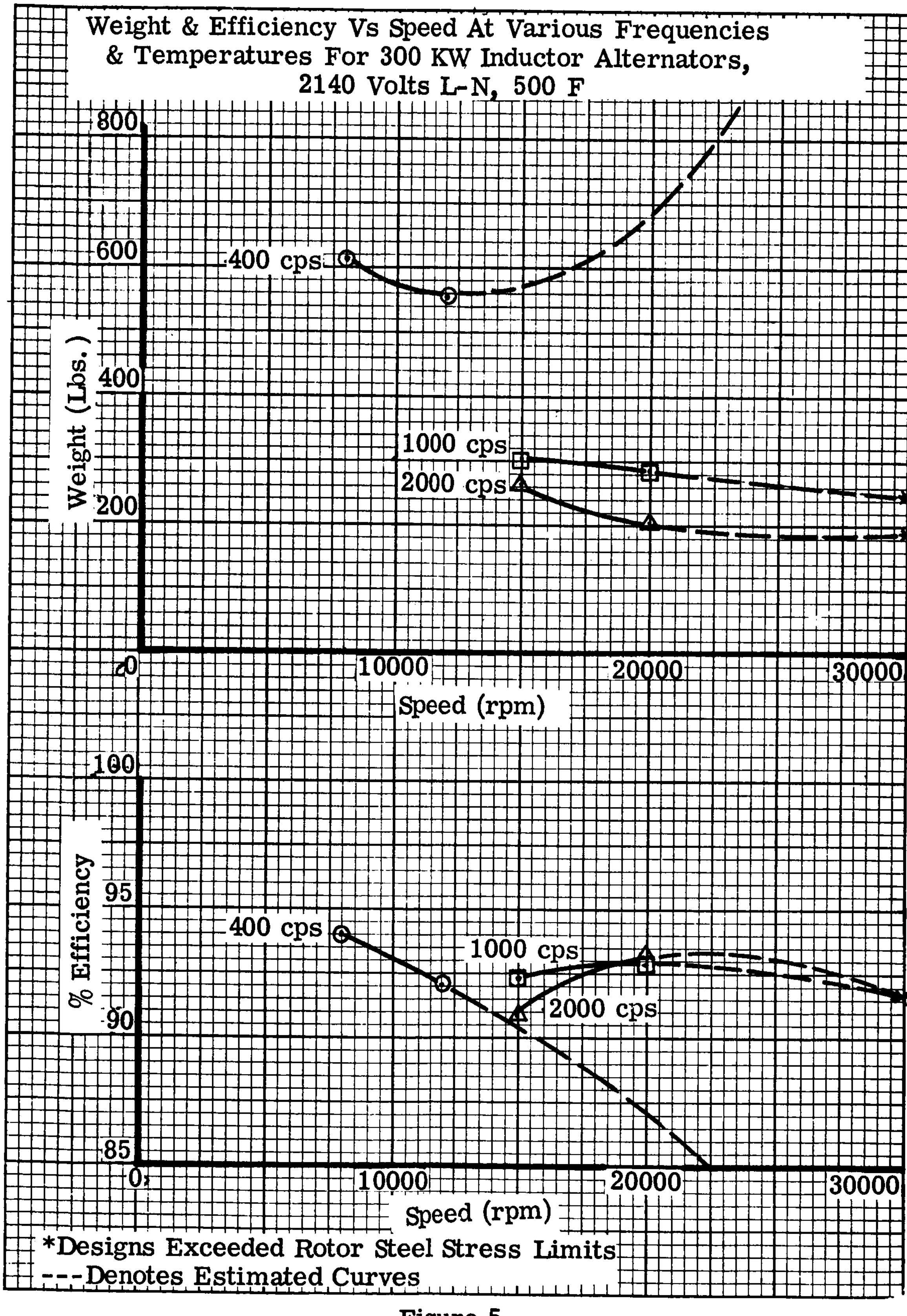

Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 300 KW Inductor Alternators,
2140 Volts L-N, 500 F
800
600
400
200
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
0
% Efficiency
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 5.

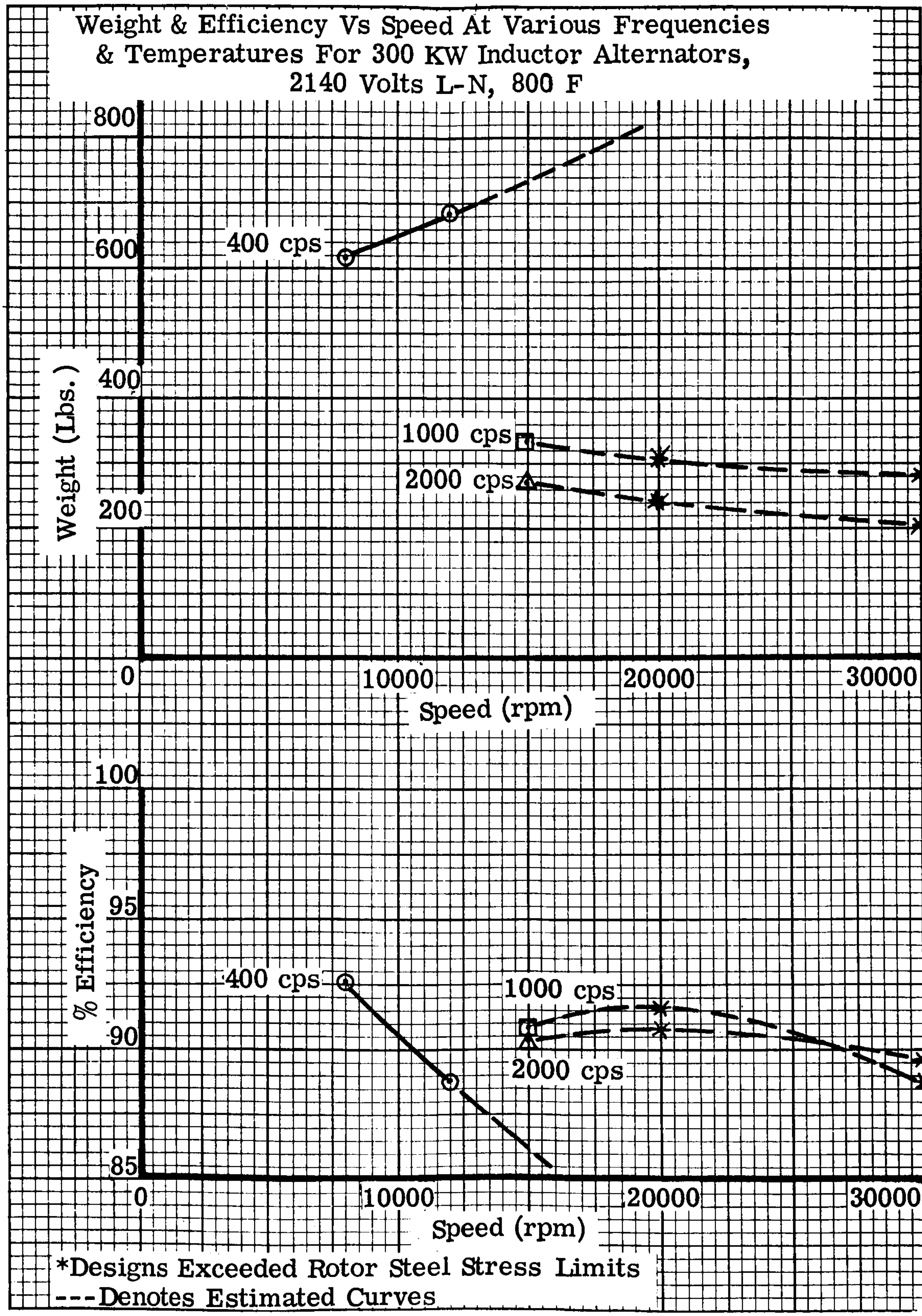
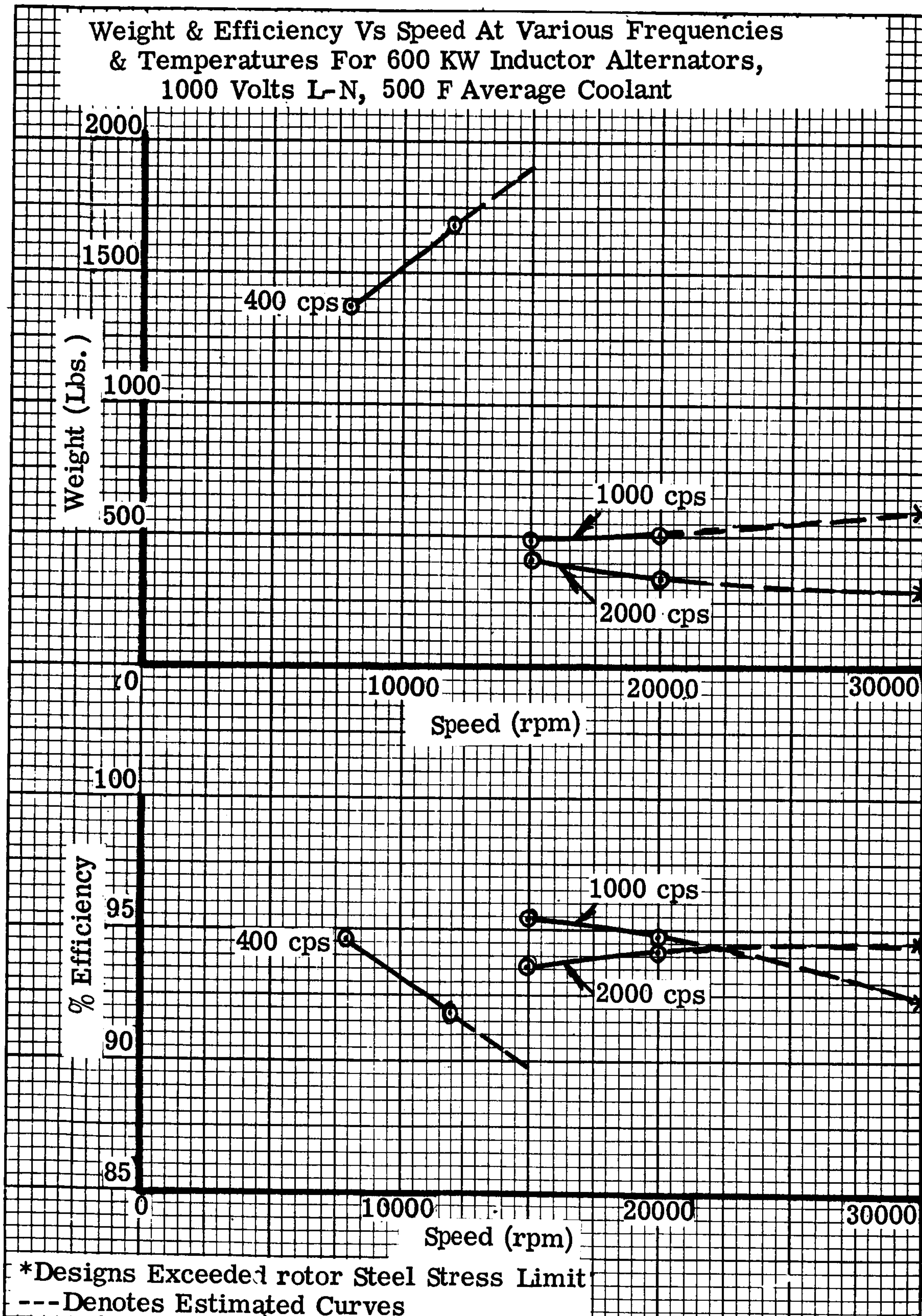
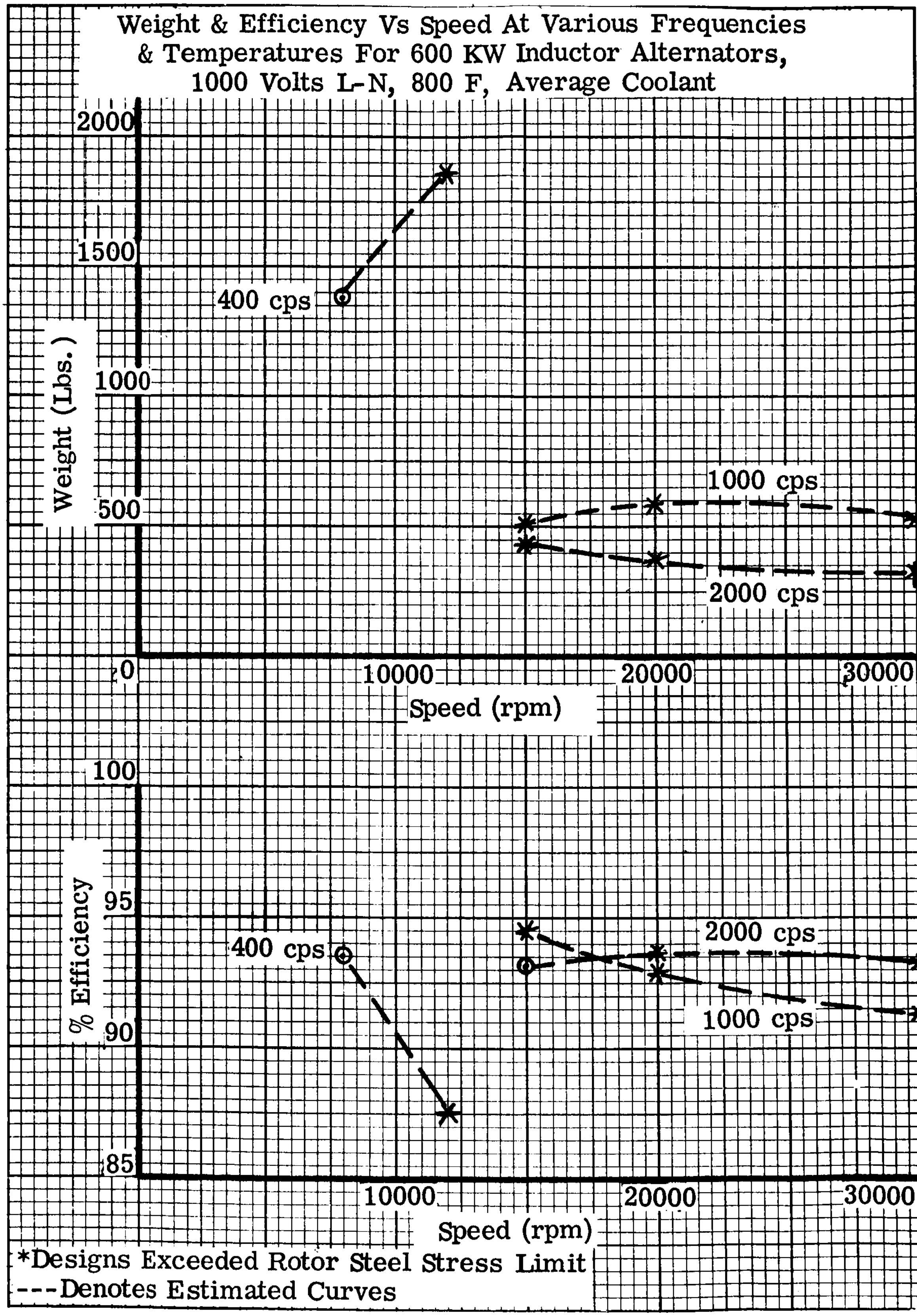

Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 300 KW Inductor Alternators,
2140 Volts L-N, 800 F
Weight (Lbs.)
800
600
400
200
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
% Efficiency
100
95
90
85
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 6.



Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 600 KW Inductor Alternators,
1000 Volts L-N, 500 F Average Coolant
2000
1500
1000
500
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
% Efficiency
400 cps
1000 cps
2000 cps
0
10000
20000
30000
Speed (rpm)
*Designs Exceeded rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 7.



Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 600 KW Inductor Alternators,
1000 Volts L-N, 800 F, Average Coolant
2000
1500
1000
500
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
% Efficiency
400 cps
2000 cps
1000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 8.

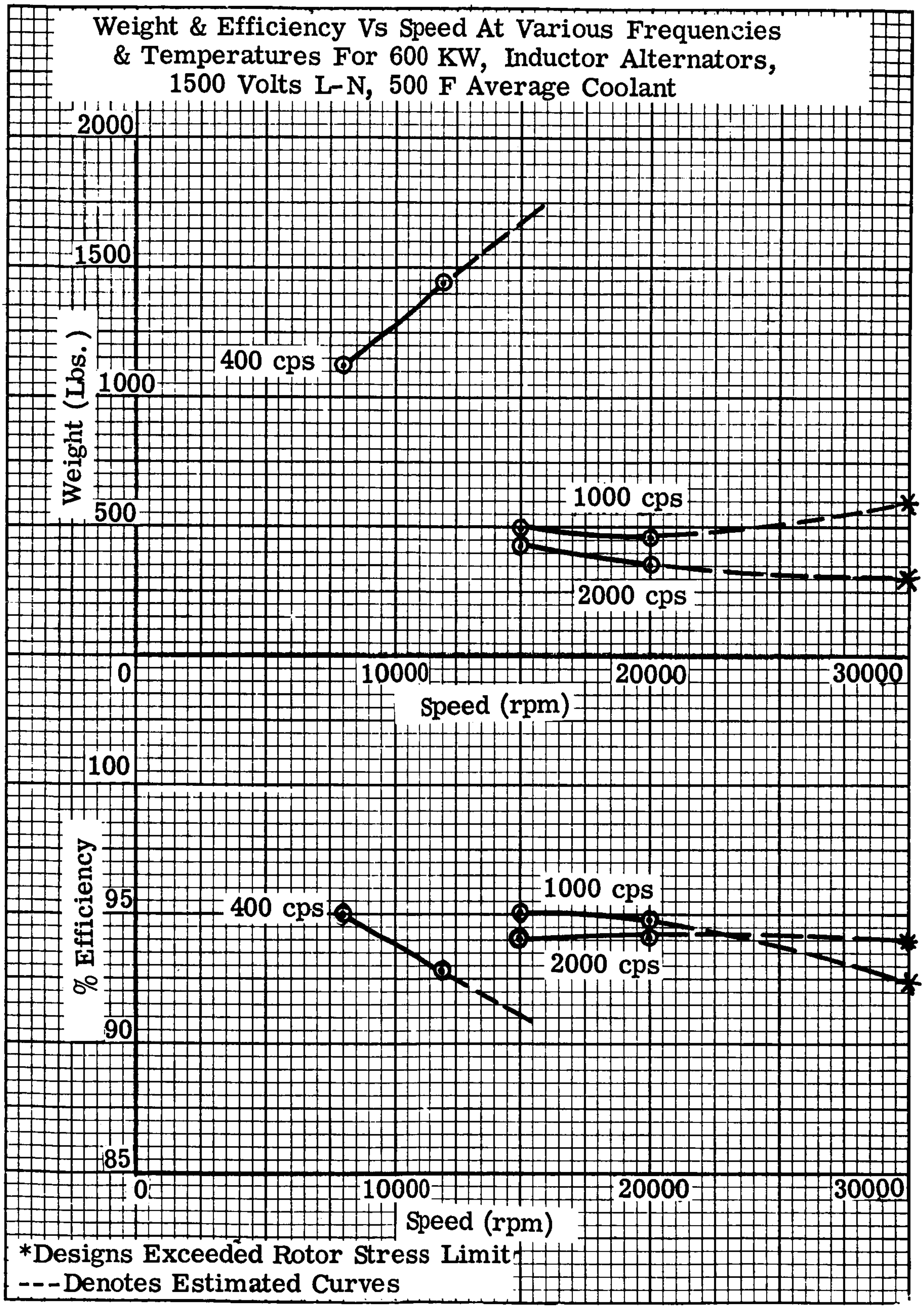
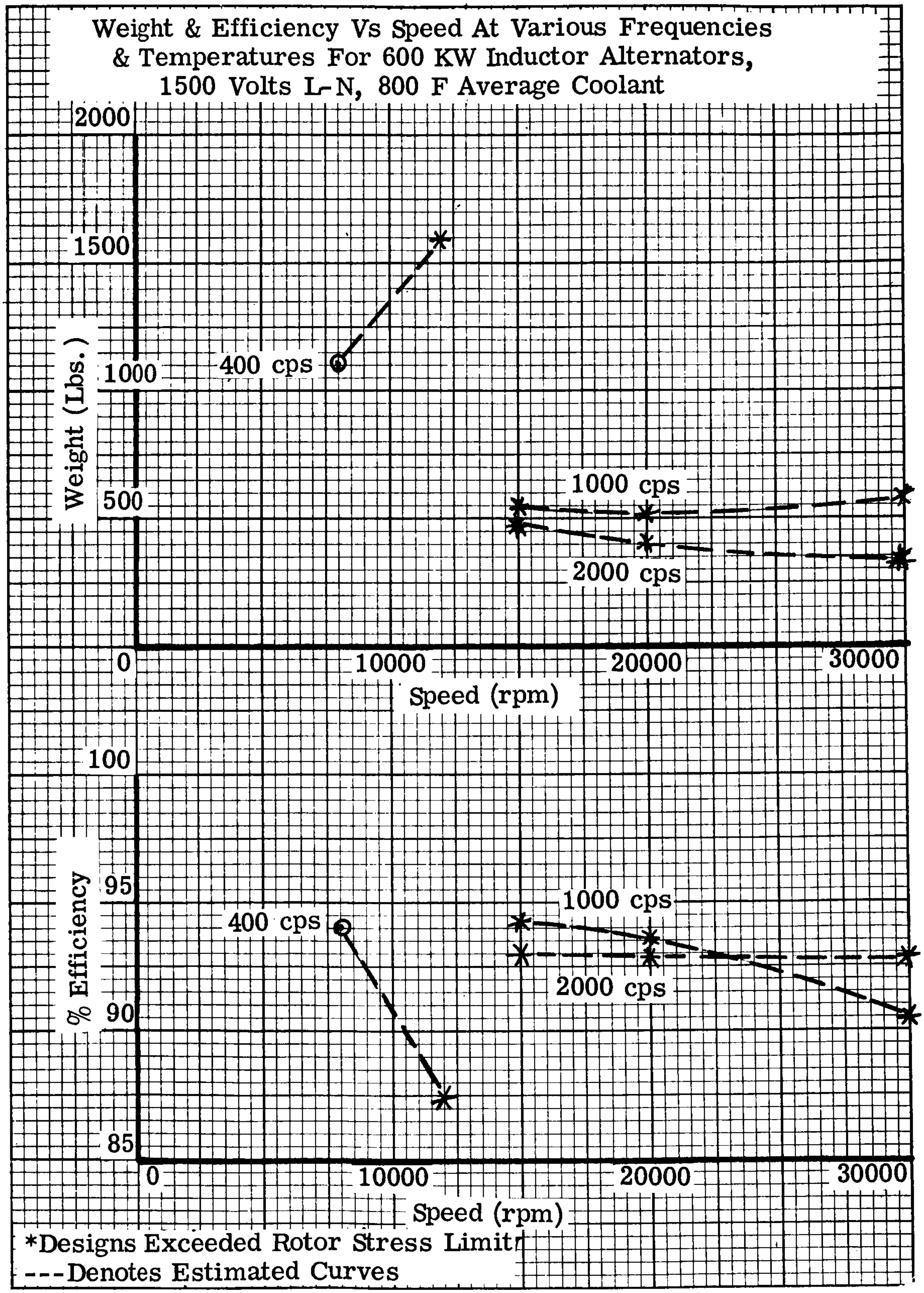

Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 600 KW, Inductor Alternators,
1500 Volts L-N, 500 F Average Coolant
Weight (Lbs.)
2000
1500
1000
500
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
% Efficiency
100
95
90
85
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Stress Limit
---Denotes Estimated Curves

Figure 9.



Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 600 KW Inductor Alternators,
1500 Volts L-N, 800 F Average Coolant
Weight (Lbs.)
2000
1500
1000
500
0
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
% Efficiency
100
95
90
85
400 cps
1000 cps
2000 cps
0
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Stress Limit
---Denotes Estimated Curves

Figure 10.

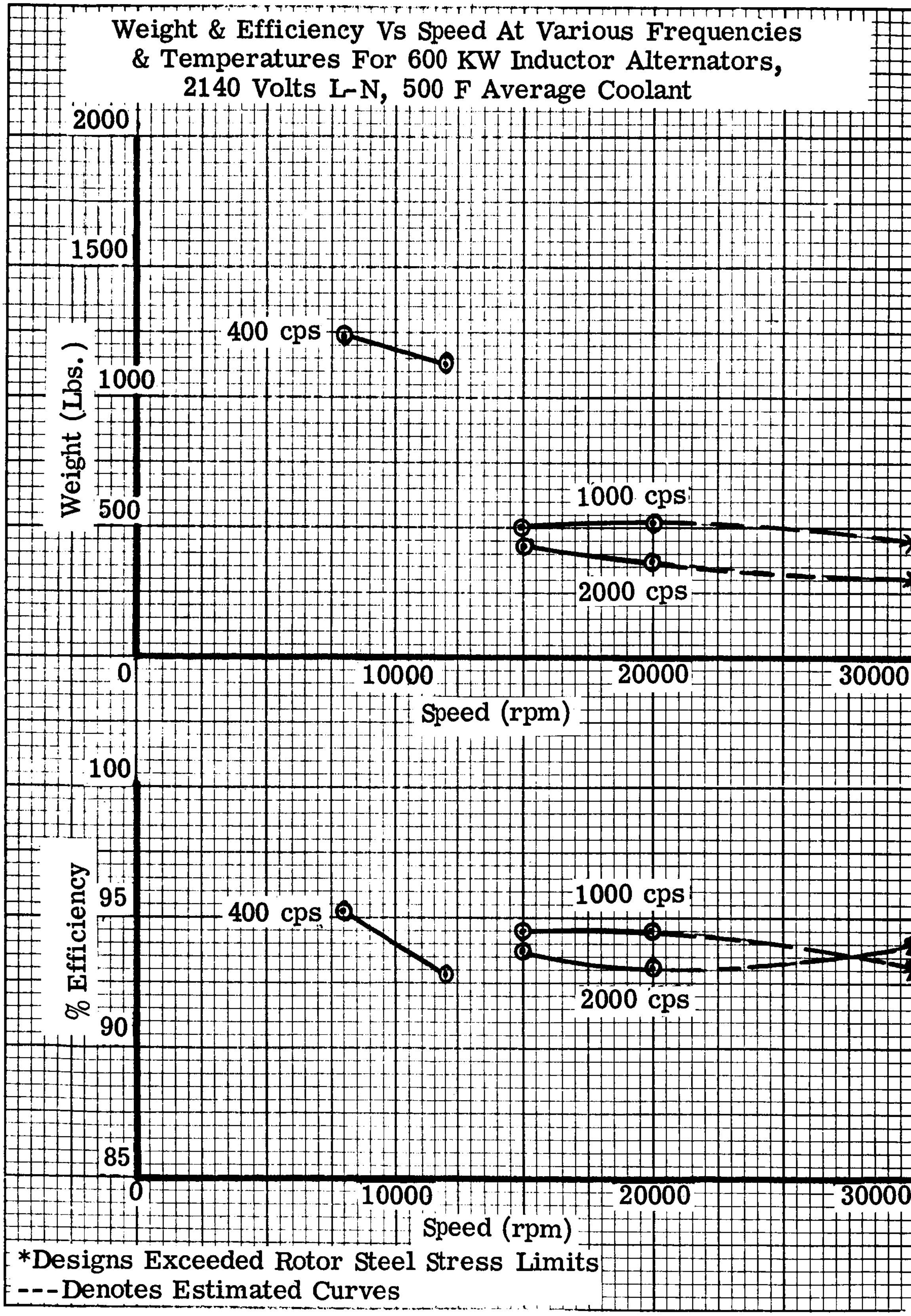

Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 600 KW Inductor Alternators,
2140 Volts L-N, 500 F Average Coolant
2000
1500
1000
500
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
0
% Efficiency
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 11.

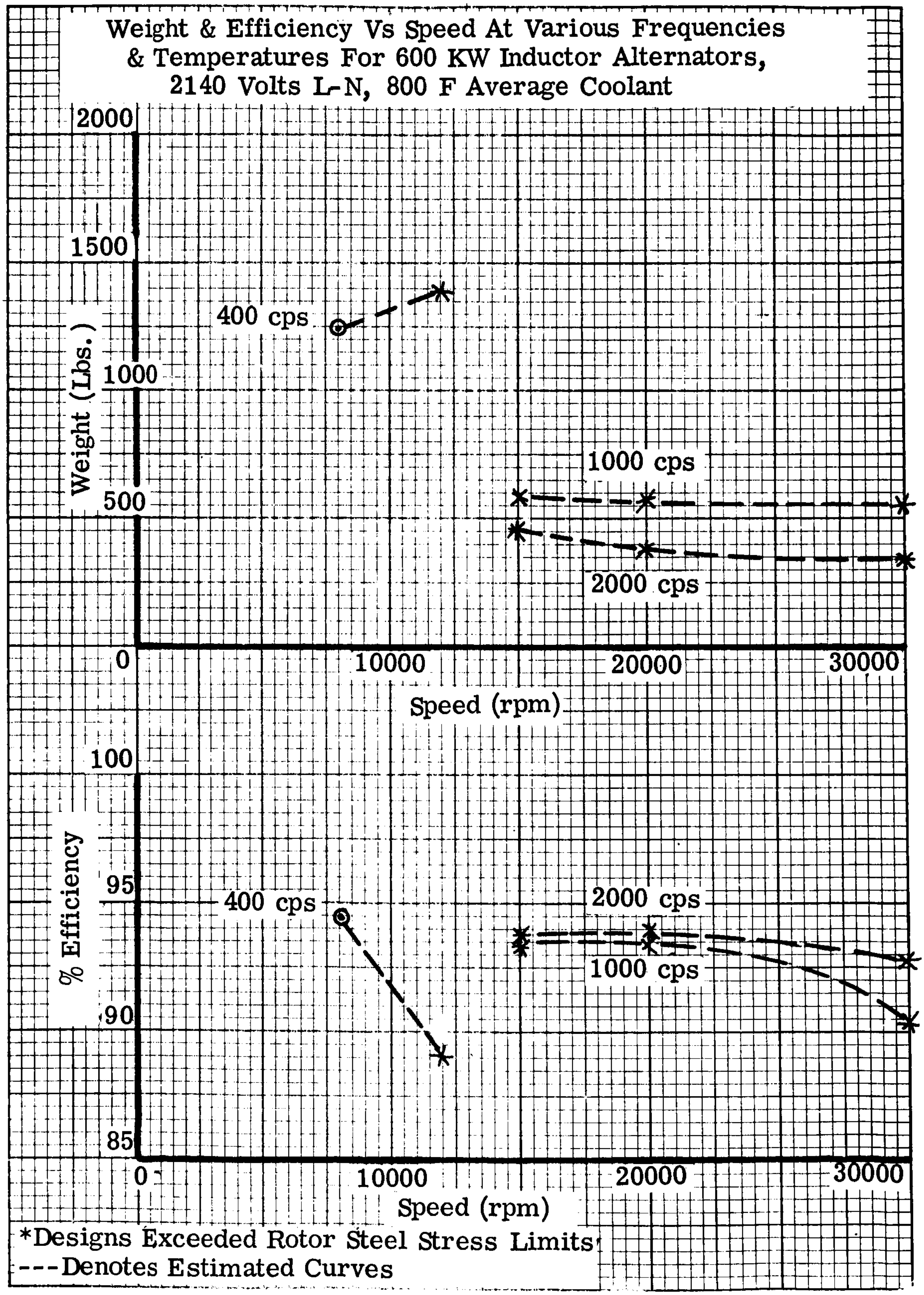
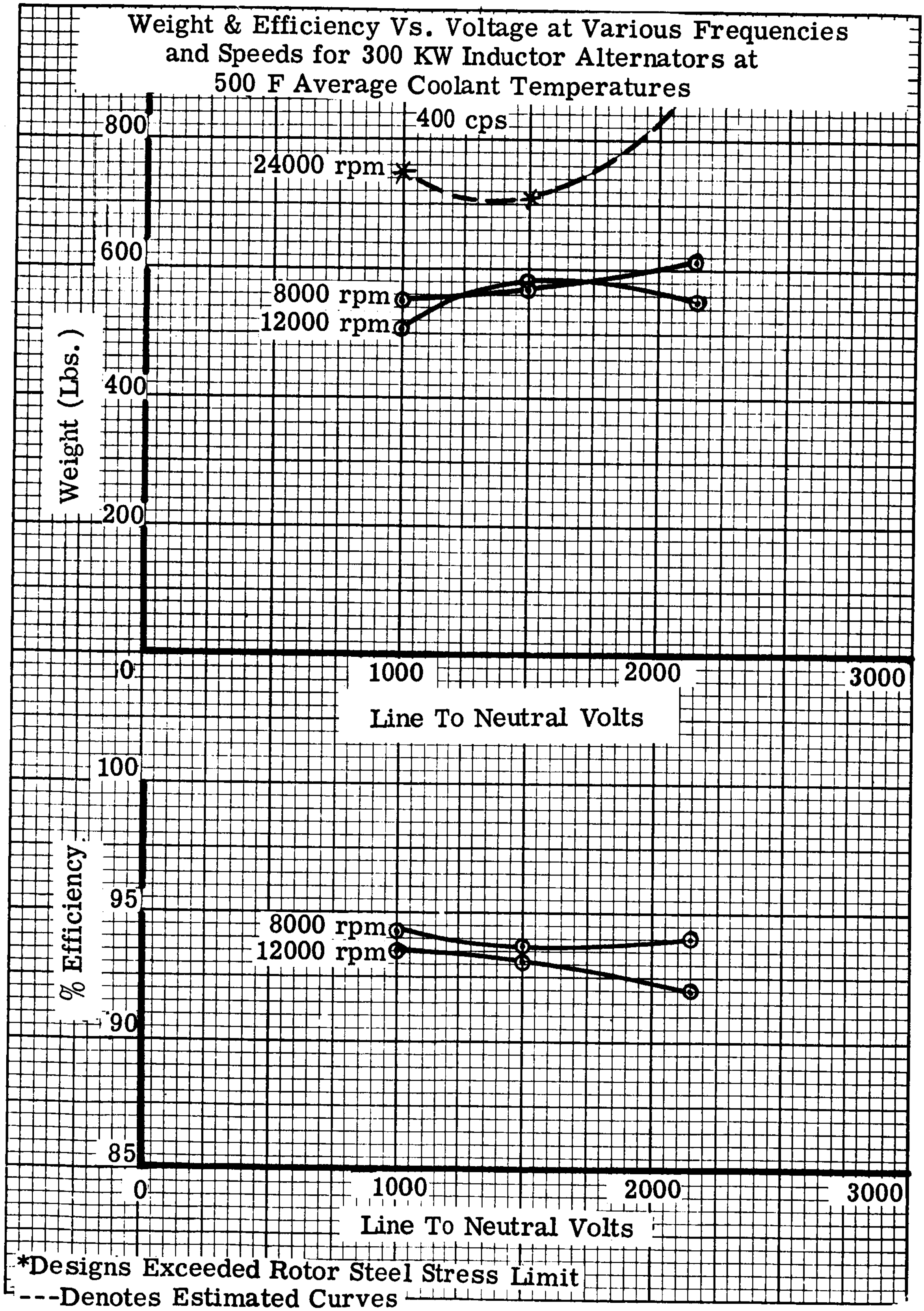
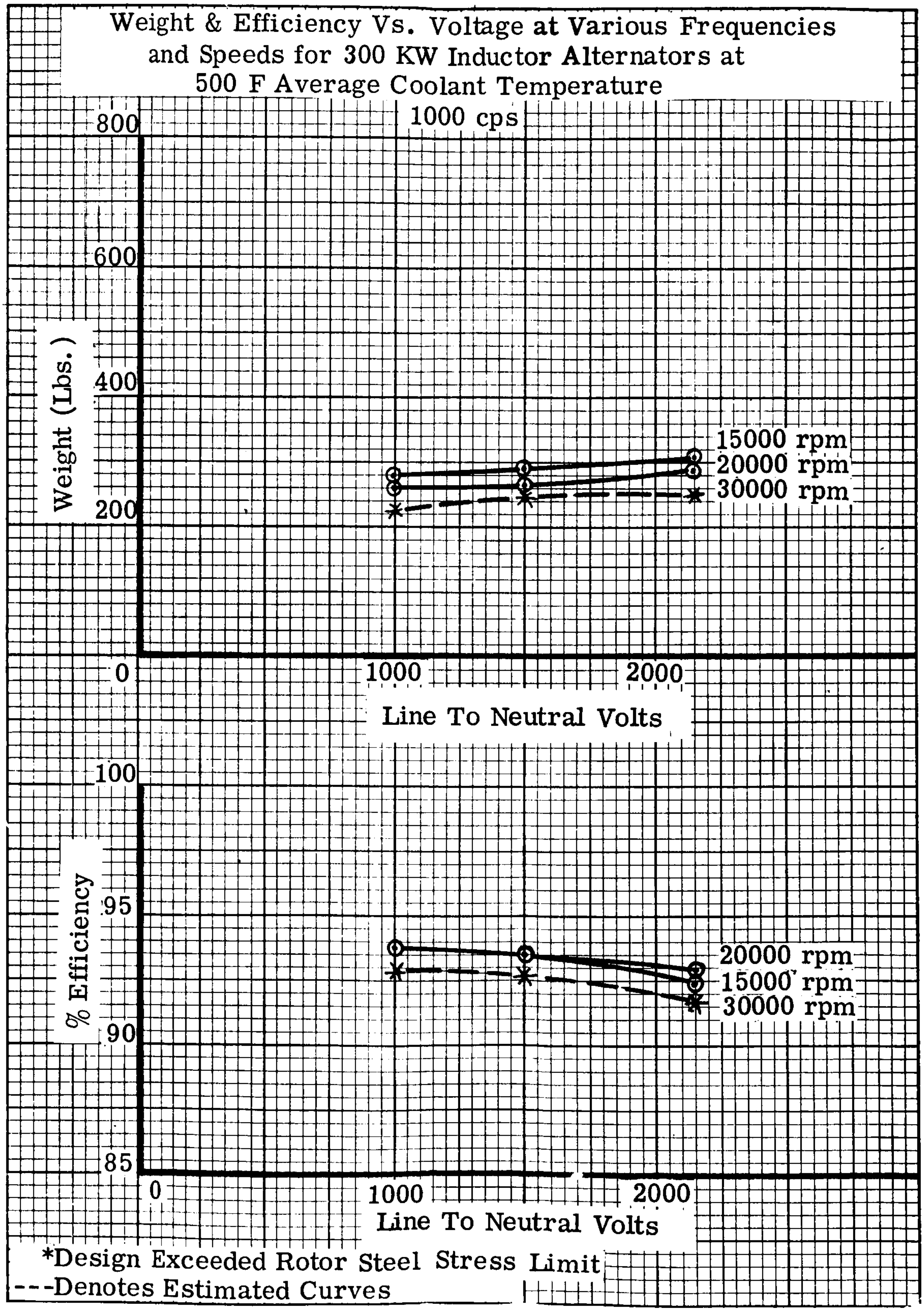

Weight & Efficiency Vs Speed At Various Frequencies
& Temperatures For 600 KW Inductor Alternators,
2140 Volts L-N, 800 F Average Coolant
2000
1500
1000
500
0
Weight (Lbs.)
400 cps
1000 cps
2000 cps
10000
20000
30000
Speed (rpm)
100
95
90
85
% Efficiency
400 cps
2000 cps
1000 cps
0
10000
20000
30000
Speed (rpm)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 12.



Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 300 KW Inductor Alternators at 500 F Average Coolant Temperatures
400 cps
24000 rpm
8000 rpm
12000 rpm
Weight (Lbs.)
800
600
400
200
0
1000
2000
3000
Line To Neutral Volts
100
95
90
85
% Efficiency
8000 rpm
12000 rpm
0
1000
2000
3000
Line To Neutral Volts
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 13.



Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 300 KW Inductor Alternators at 500 F Average Coolant Temperature
1000 cps
Weight (Lbs.)
800
600
400
200
0
1000
2000
Line To Neutral Volts
15000 rpm
20000 rpm
30000 rpm
% Efficiency
100
95
90
85
0
1000
2000
Line To Neutral Volts
20000 rpm
15000 rpm
30000 rpm
*Design Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 14.

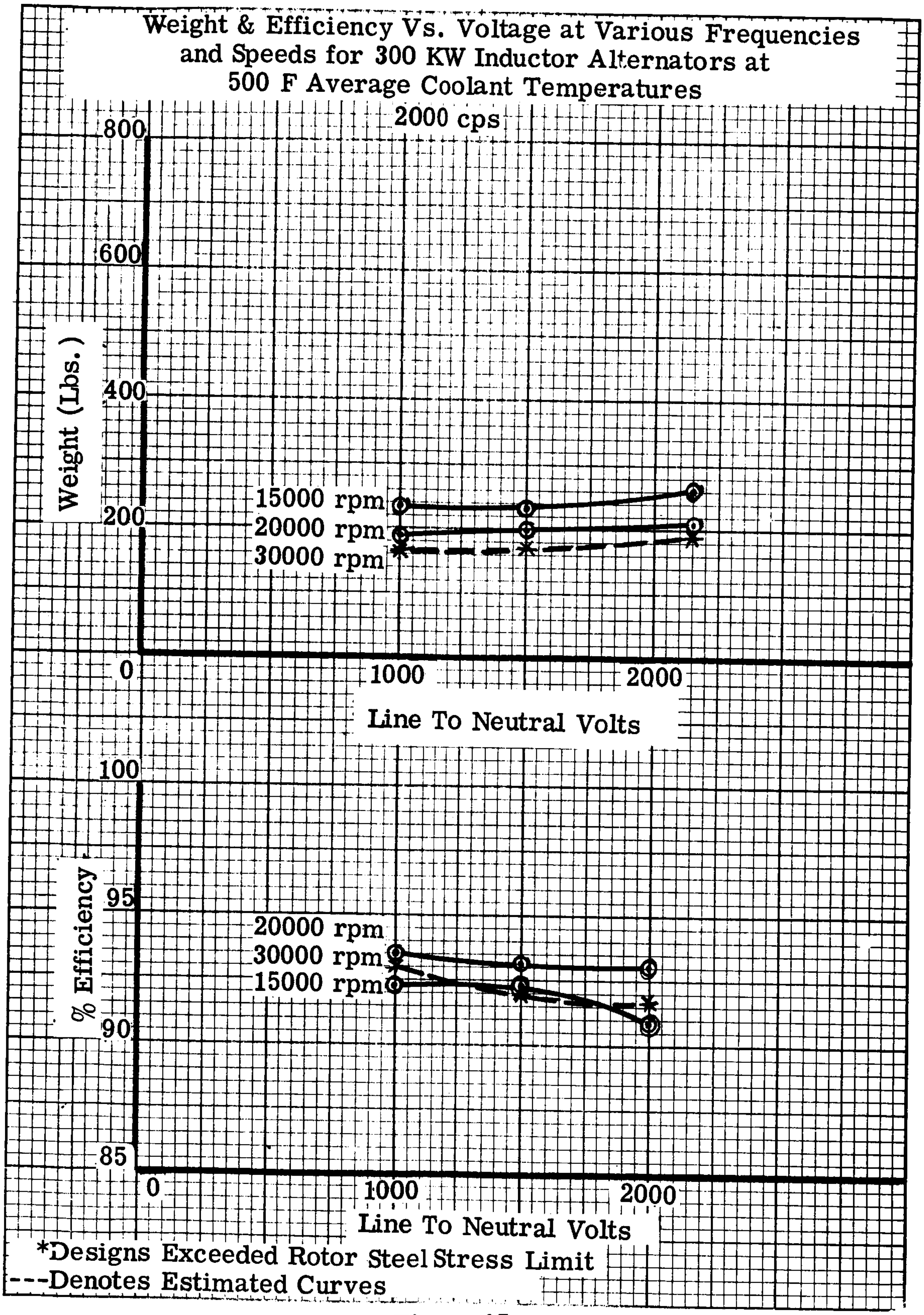
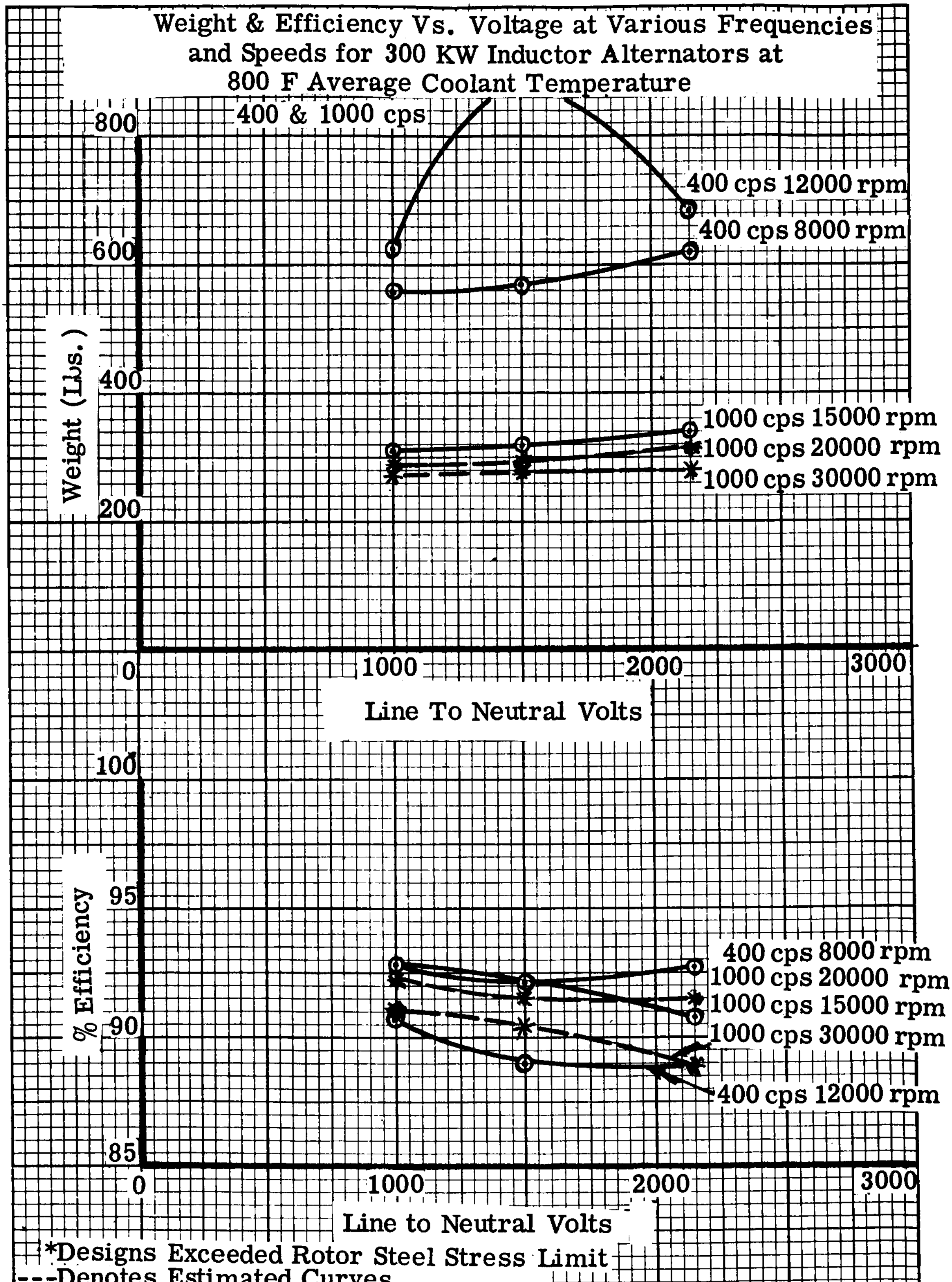
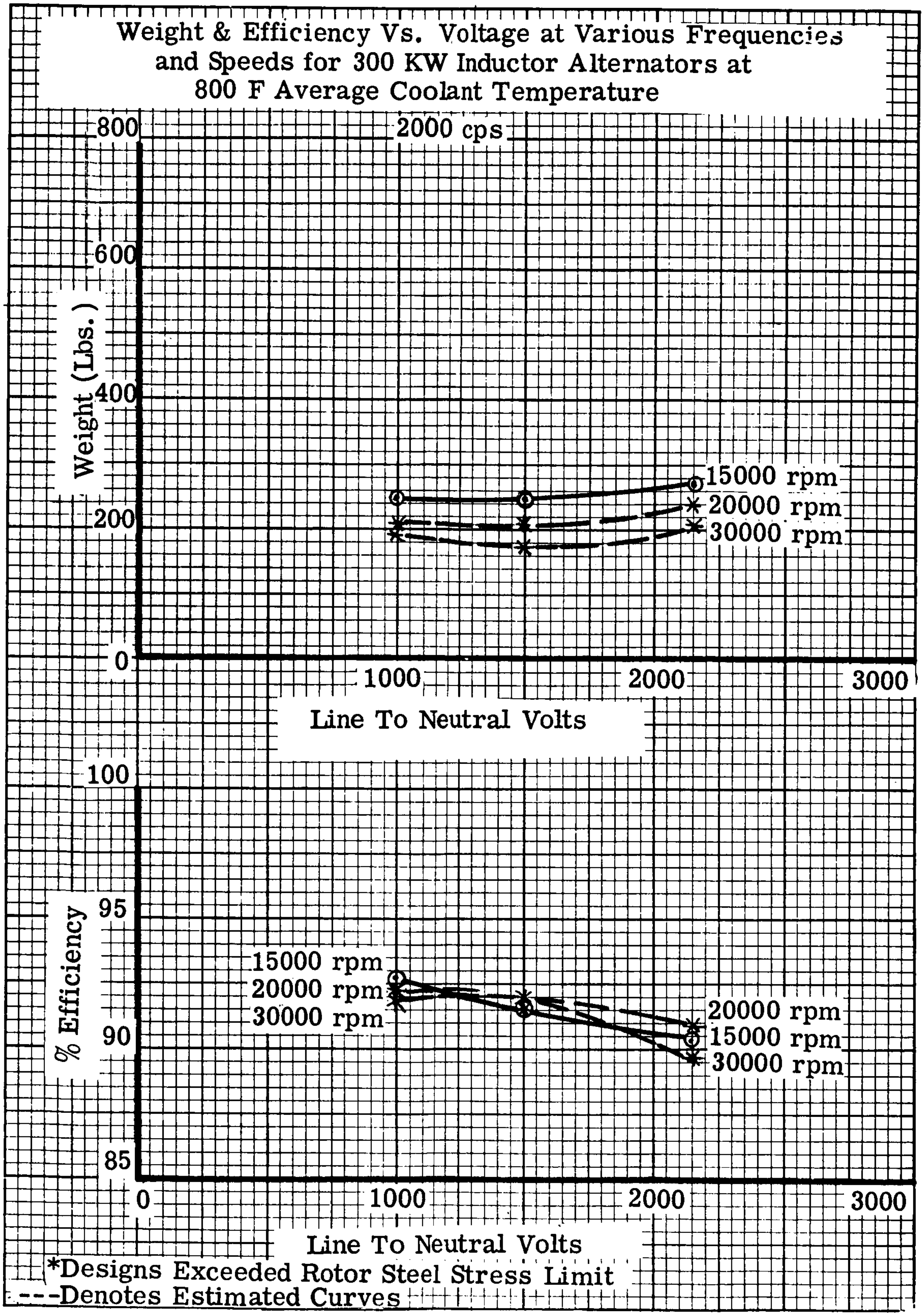

Weight & Efficiency Vs. Voltage at Various Frequencies
and Speeds for 300 KW Inductor Alternators at
500 F Average Coolant Temperatures
2000 cps
800
600
400
200
0
Weight (Lbs.)
15000 rpm
20000 rpm
30000 rpm
1000
2000
Line To Neutral Volts
100
95
90
85
% Efficiency
20000 rpm
30000 rpm
15000 rpm
0
1000
2000
Line To Neutral Volts
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 15.



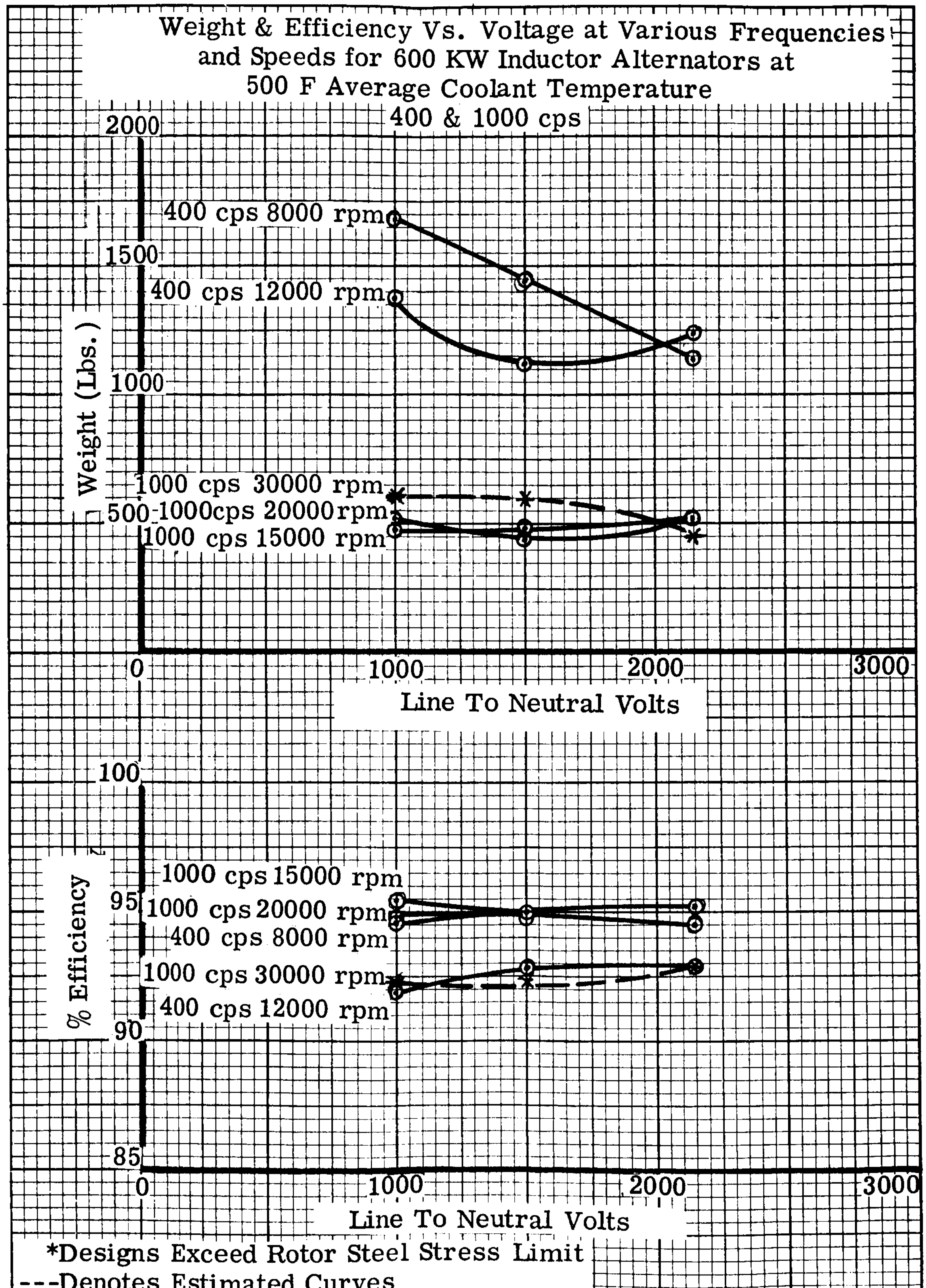
Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 300 KW Inductor Alternators at 800 F Average Coolant Temperature
400 & 1000 cps
Weight (Lbs.)
800
600
400
200
0
400 cps 12000 rpm
400 cps 8000 rpm
1000 cps 15000 rpm
1000 cps 20000 rpm
1000 cps 30000 rpm
1000
2000
3000
Line To Neutral Volts
% Efficiency
100
95
90
85
400 cps 8000 rpm
1000 cps 20000 rpm
1000 cps 15000 rpm
1000 cps 30000 rpm
400 cps 12000 rpm
0
1000
2000
3000
Line to Neutral Volts
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 16.



Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 300 KW Inductor Alternators at 800 F Average Coolant Temperature
2000 cps
Weight (Lbs.)
800
600
400
200
0
1000
2000
3000
Line To Neutral Volts
15000 rpm
20000 rpm
30000 rpm
% Efficiency
100
95
90
85
0
1000
2000
3000
Line To Neutral Volts
15000 rpm
20000 rpm
30000 rpm
20000 rpm
15000 rpm
30000 rpm
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 17.



Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 600 KW Inductor Alternators at 500 F Average Coolant Temperature
400 & 1000 cps
Weight (Lbs.)
2000
1500
1000
500
0
400 cps 8000 rpm
400 cps 12000 rpm
1000 cps 30000 rpm
1000cps 20000rpm
1000 cps 15000 rpm
1000
2000
3000
Line To Neutral Volts
% Efficiency
100
95
90
85
1000 cps 15000 rpm
1000 cps 20000 rpm
400 cps 8000 rpm
1000 cps 30000 rpm
400 cps 12000 rpm
0
1000
2000
3000
Line To Neutral Volts
*Designs Exceed Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 18.

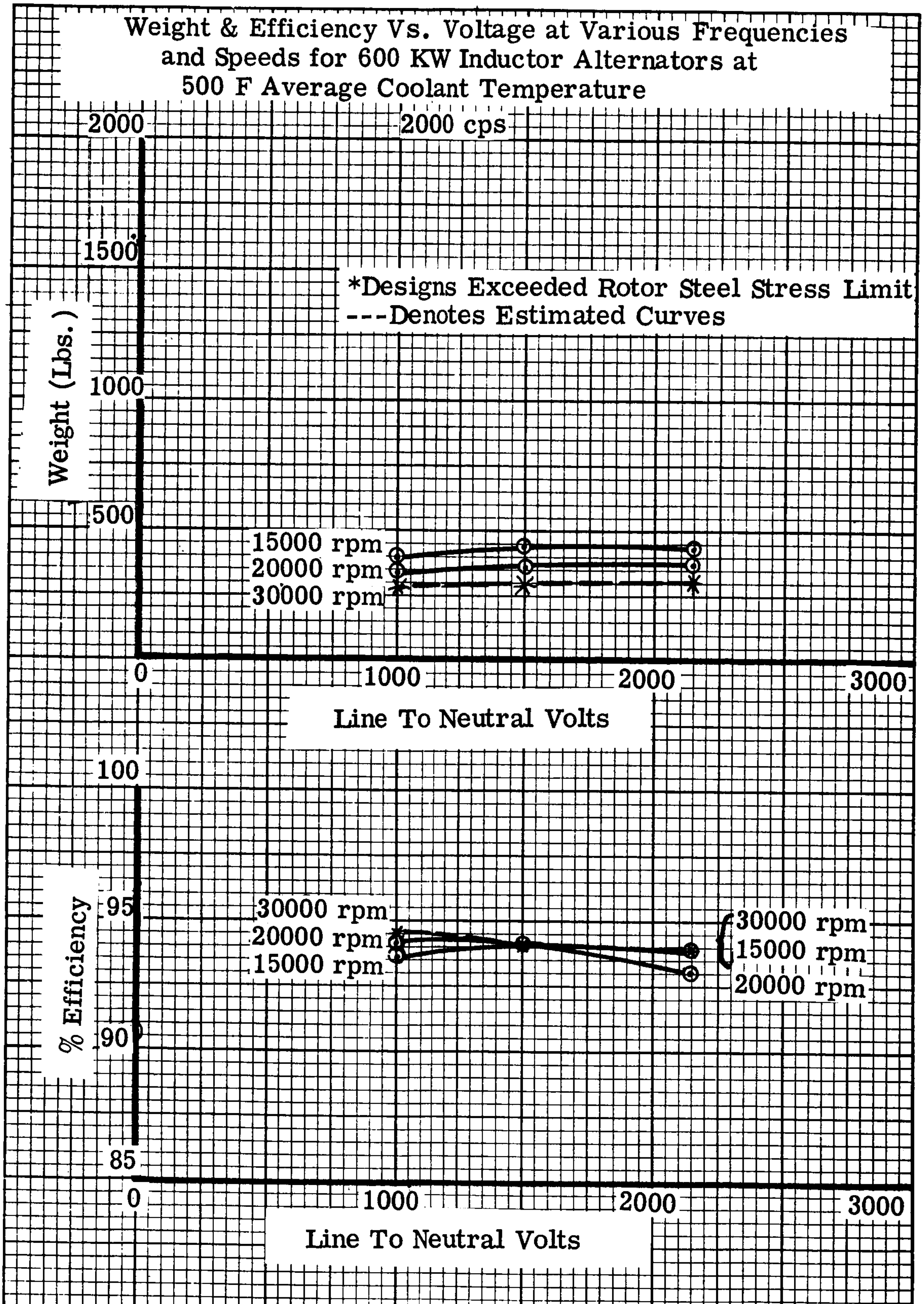
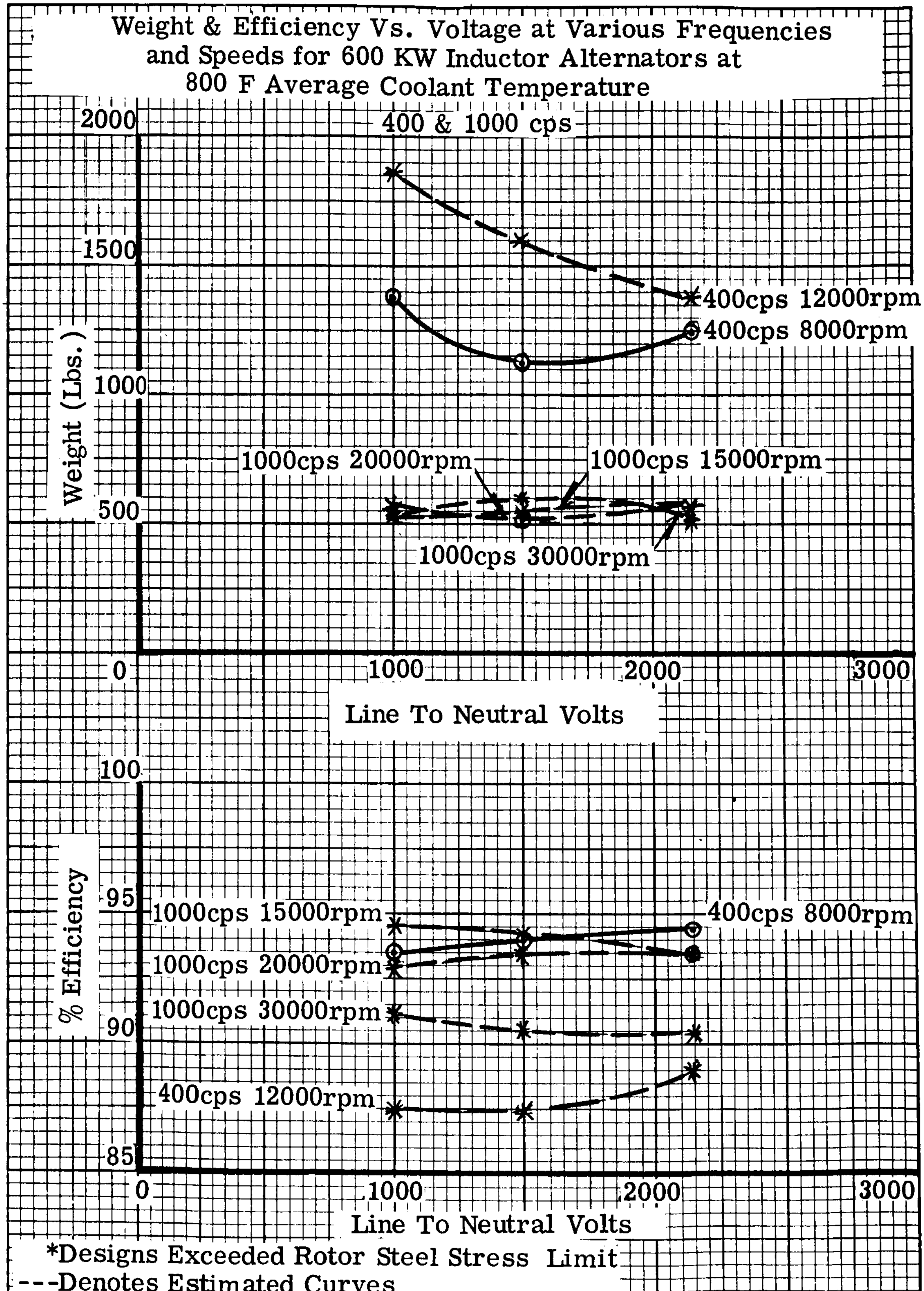
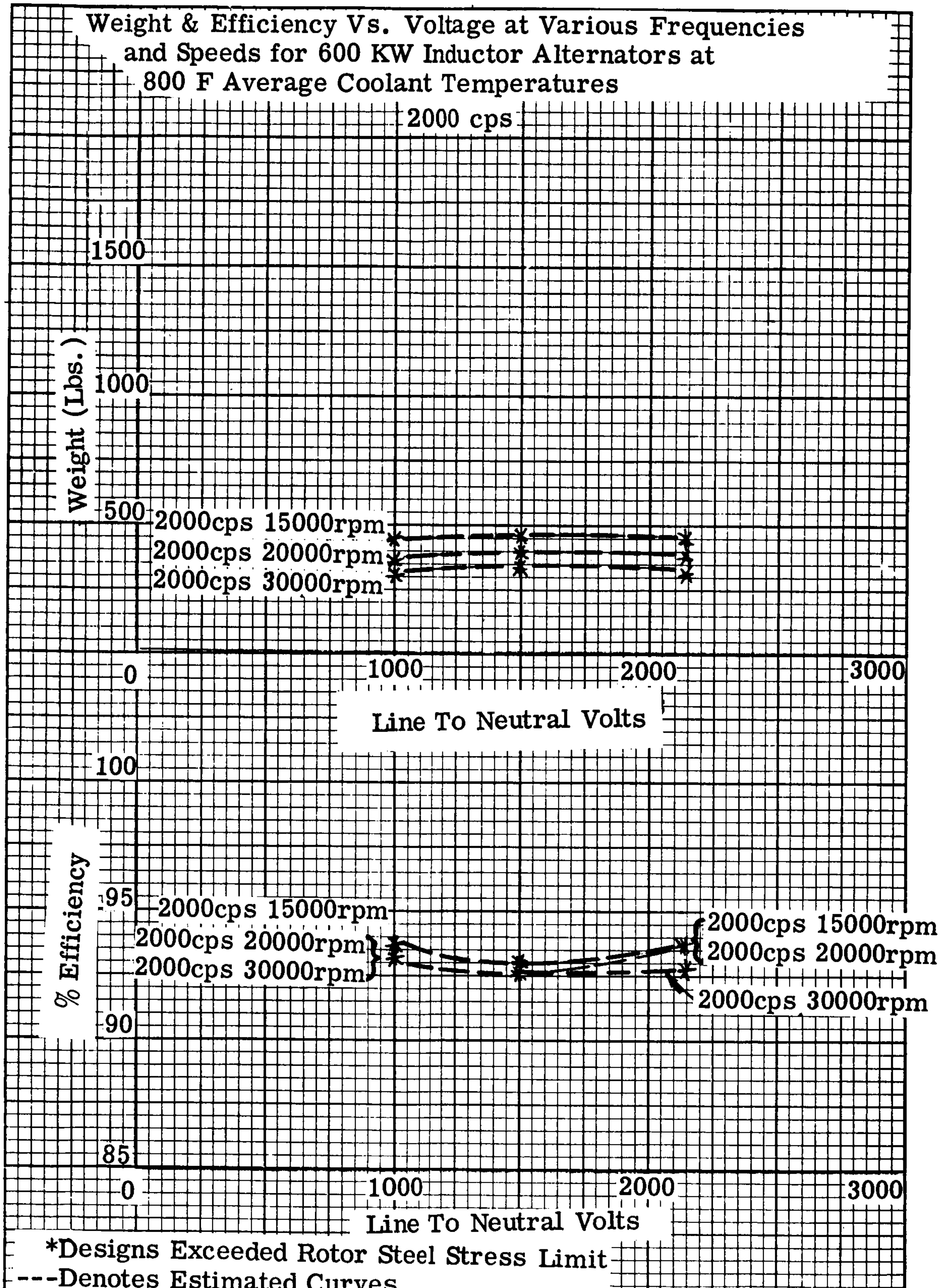

Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 600 KW Inductor Alternators at 500 F Average Coolant Temperature
2000 cps
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves
Weight (Lbs.)
2000
1500
1000
500
0
15000 rpm
20000 rpm
30000 rpm
1000
2000
3000
Line To Neutral Volts
100
95
90
85
0
% Efficiency
30000 rpm
20000 rpm
15000 rpm
30000 rpm
15000 rpm
20000 rpm
1000
2000
3000
Line To Neutral Volts

Figure 19.



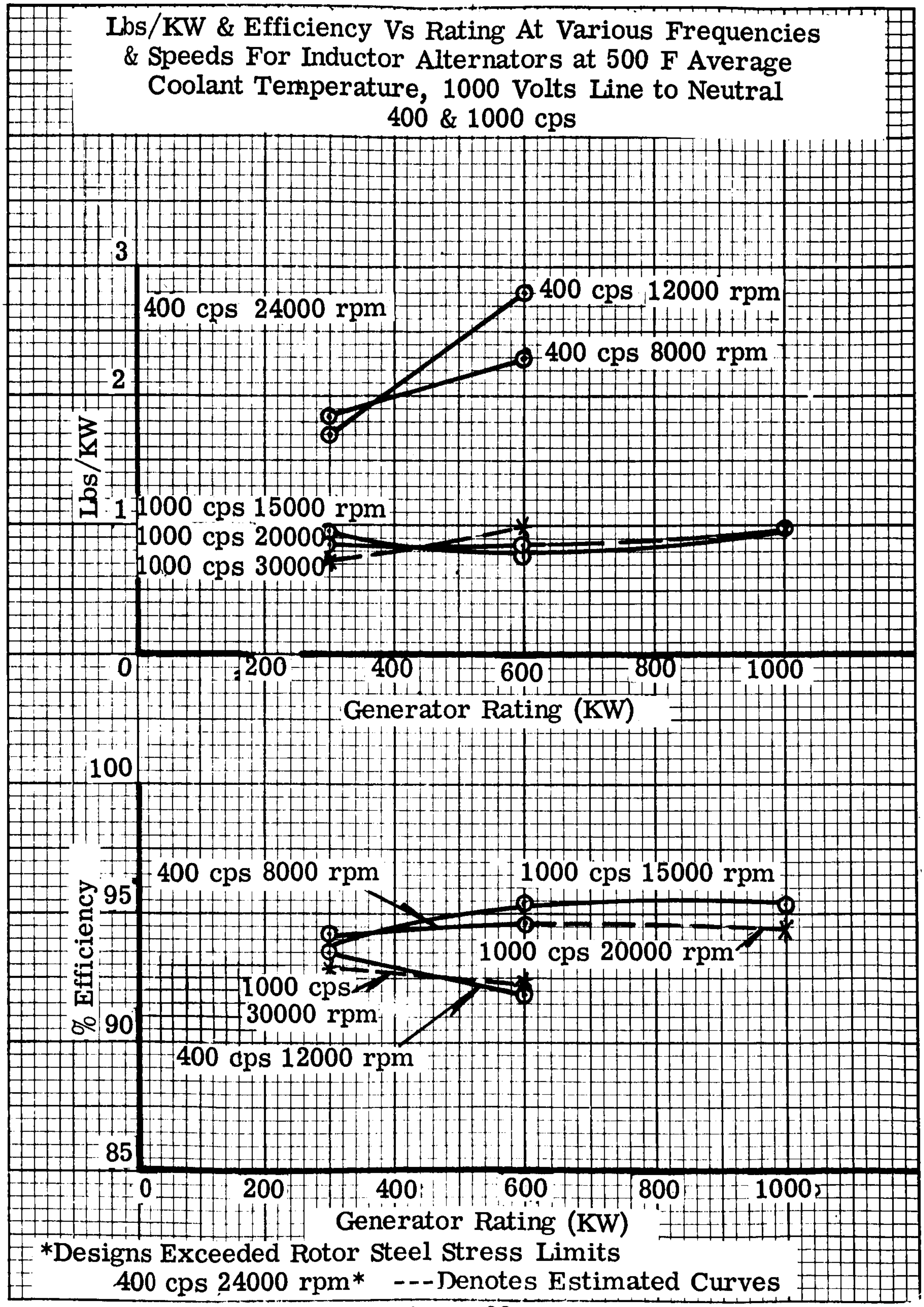
Weight & Efficiency Vs. Voltage at Various Frequencies and Speeds for 600 KW Inductor Alternators at 800 F Average Coolant Temperature
400 & 1000 cps
Weight (Lbs.)
2000
1500
1000
500
0
400cps 12000rpm
400cps 8000rpm
1000cps 20000rpm
1000cps 15000rpm
1000cps 30000rpm
1000
2000
3000
Line To Neutral Volts
% Efficiency
100
95
90
85
0
1000cps 15000rpm
1000cps 20000rpm
1000cps 30000rpm
400cps 12000rpm
400cps 8000rpm
1000
2000
3000
Line To Neutral Volts
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 20.



Weight & Efficiency Vs. Voltage at Various Frequencies
and Speeds for 600 KW Inductor Alternators at
800 F Average Coolant Temperatures
2000 cps
1500
1000
500
0
Weight (Lbs.)
2000cps 15000rpm
2000cps 20000rpm
2000cps 30000rpm
1000
2000
3000
Line To Neutral Volts
100
95
90
85
0
% Efficiency
2000cps 15000rpm
2000cps 20000rpm
2000cps 30000rpm
2000cps 15000rpm
2000cps 20000rpm
2000cps 30000rpm
1000
2000
3000
Line To Neutral Volts
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 21.



Lbs/KW & Efficiency Vs Rating At Various Frequencies
& Speeds For Inductor Alternators at 500 F Average
Coolant Temperature, 1000 Volts Line to Neutral
400 & 1000 cps
Lbs/KW
3
2
1
0
400 cps 24000 rpm
400 cps 12000 rpm
400 cps 8000 rpm
1000 cps 15000 rpm
1000 cps 20000
1000 cps 30000*
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
400 cps 8000 rpm
1000 cps 15000 rpm
1000 cps 20000 rpm
1000 cps
30000 rpm
400 cps 12000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limits
400 cps 24000 rpm* ---Denotes Estimated Curves

Figure 22.

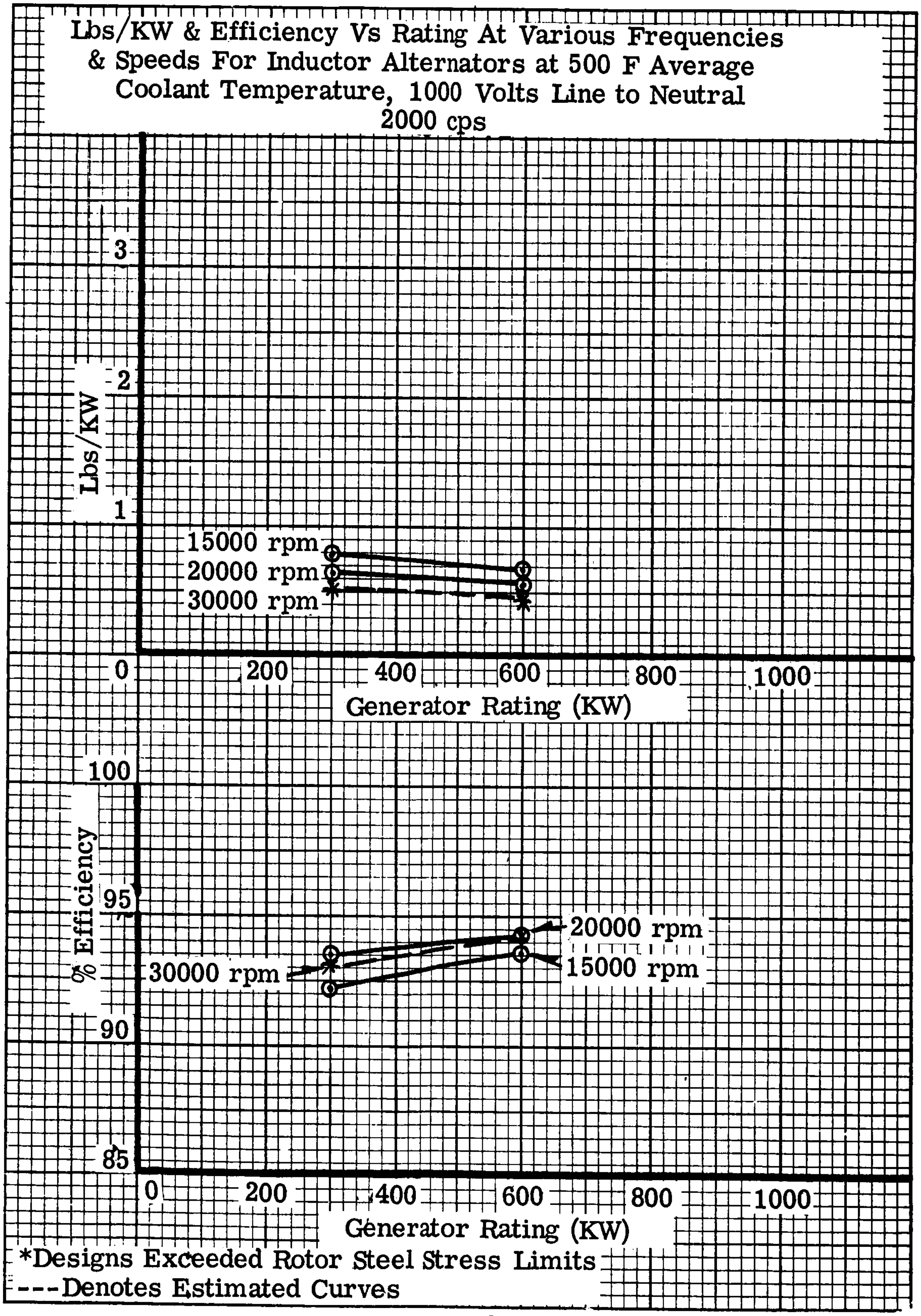

Lbs/KW & Efficiency Vs Rating At Various Frequencies
& Speeds For Inductor Alternators at 500 F Average
Coolant Temperature, 1000 Volts Line to Neutral
2000 cps
Lbs/KW
3
2
1
0
15000 rpm
20000 rpm
30000 rpm
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
20000 rpm
30000 rpm
15000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 23.

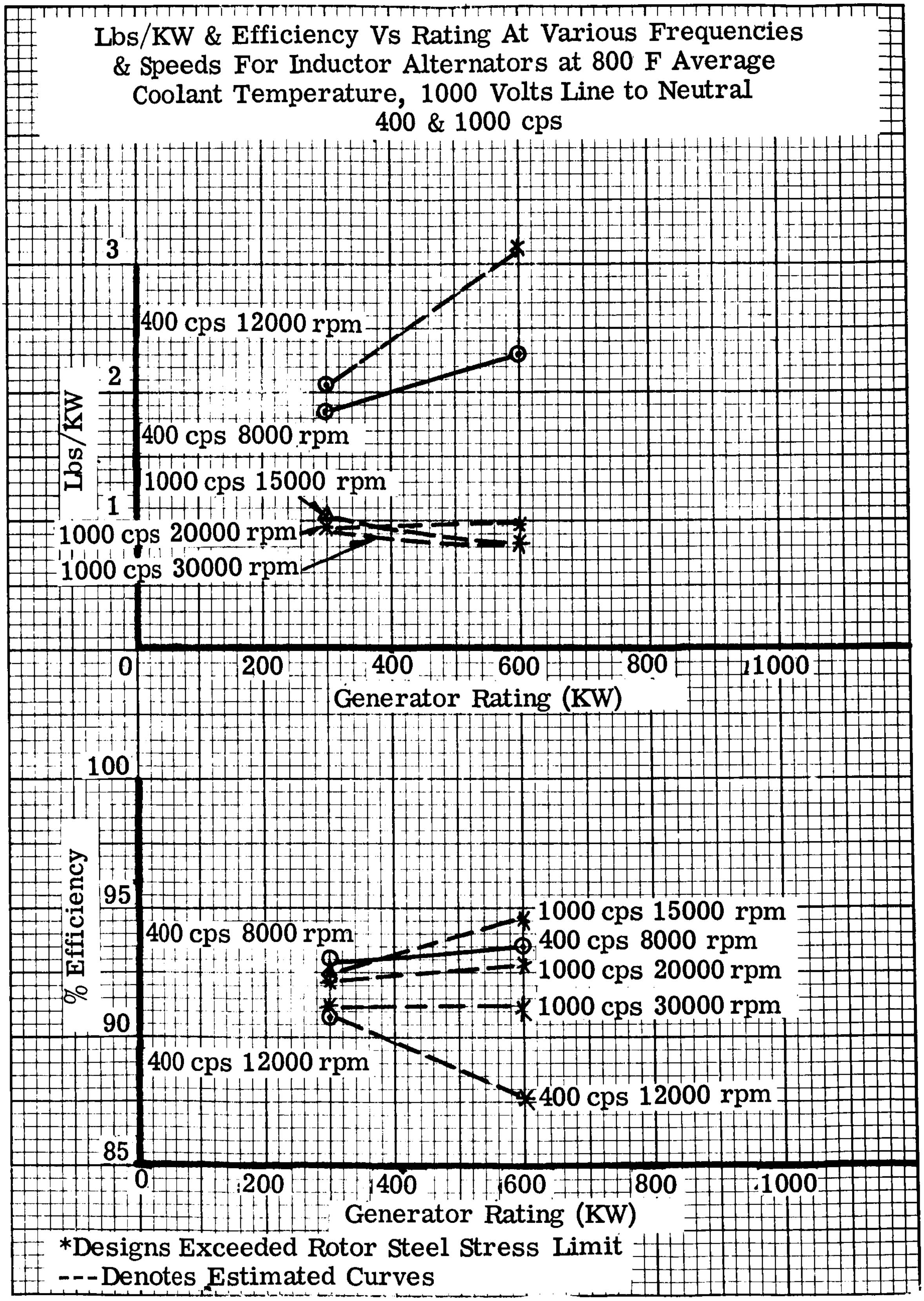
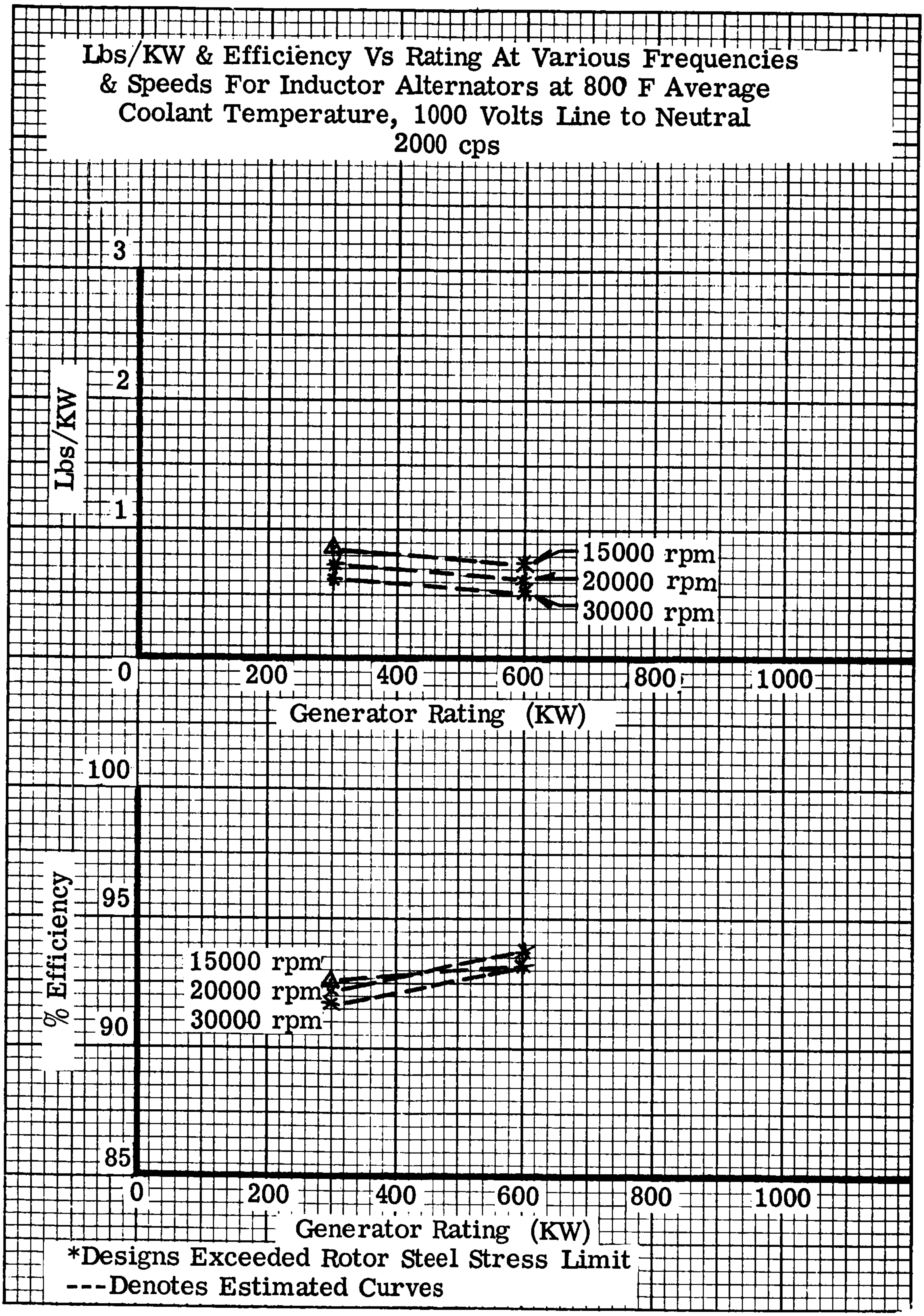
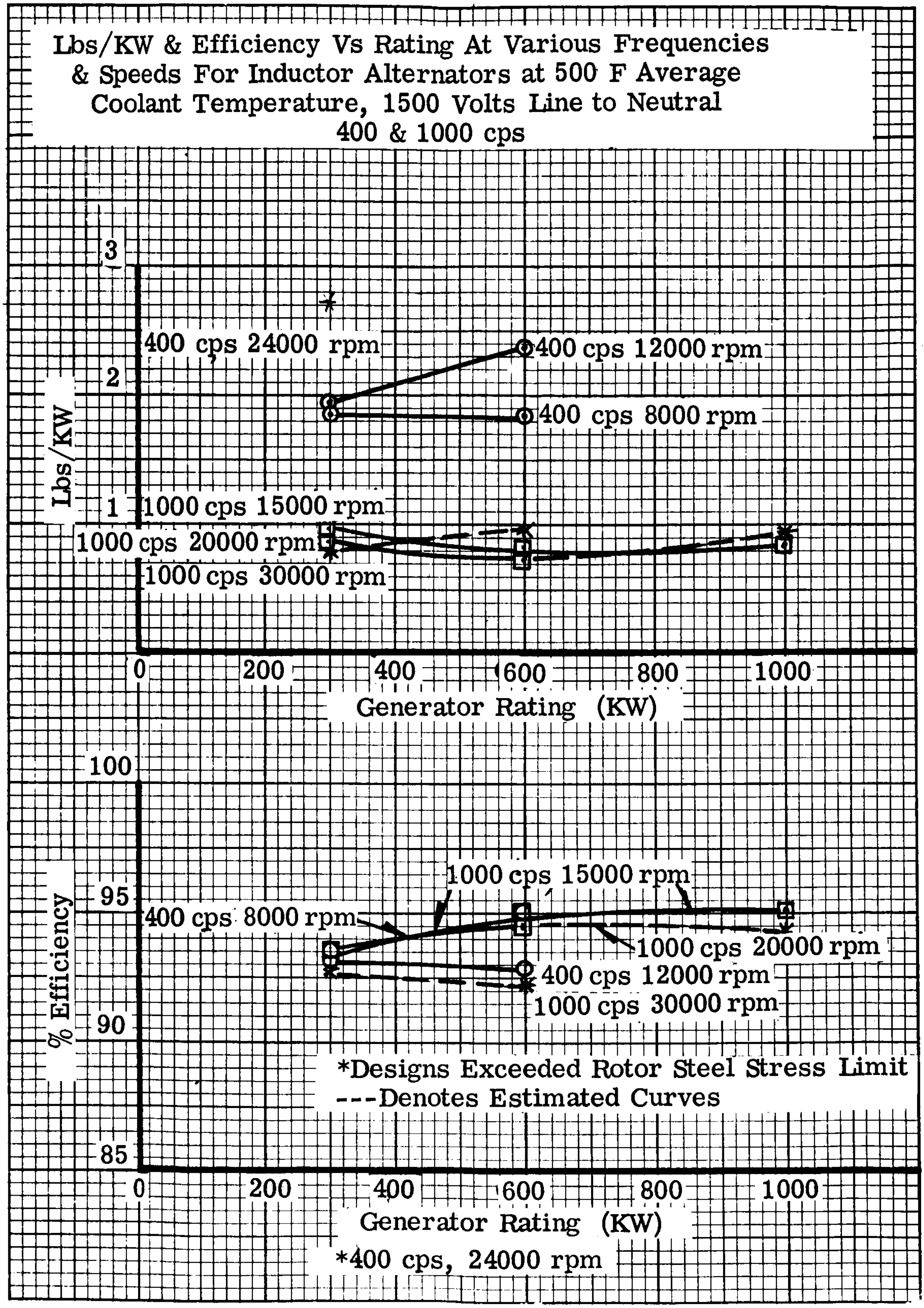

Lbs/KW & Efficiency Vs Rating At Various Frequencies & Speeds For Inductor Alternators at 800 F Average Coolant Temperature, 1000 Volts Line to Neutral
400 & 1000 cps
Lbs/KW
3
2
1
0
400 cps 12000 rpm
400 cps 8000 rpm
1000 cps 15000 rpm
1000 cps 20000 rpm
1000 cps 30000 rpm
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
400 cps 8000 rpm
400 cps 12000 rpm
1000 cps 15000 rpm
400 cps 8000 rpm
1000 cps 20000 rpm
1000 cps 30000 rpm
400 cps 12000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 24.



Lbs/KW & Efficiency Vs Rating At Various Frequencies & Speeds For Inductor Alternators at 800 F Average Coolant Temperature, 1000 Volts Line to Neutral
2000 cps
Lbs/KW
3
2
1
0
15000 rpm
20000 rpm
30000 rpm
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
15000 rpm
20000 rpm
30000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 25.



Lbs/KW & Efficiency Vs Rating At Various Frequencies & Speeds For Inductor Alternators at 500 F Average Coolant Temperature, 1500 Volts Line to Neutral
400 & 1000 cps
3
2
1
Lbs/KW
400 cps 24000 rpm
400 cps 12000 rpm
400 cps 8000 rpm
1000 cps 15000 rpm
1000 cps 20000 rpm
1000 cps 30000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
100
95
90
85
% Efficiency
1000 cps 15000 rpm
400 cps 8000 rpm
1000 cps 20000 rpm
400 cps 12000 rpm
1000 cps 30000 rpm
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves
0
200
400
600
800
1000
Generator Rating (KW)
*400 cps, 24000 rpm

Figure 26.

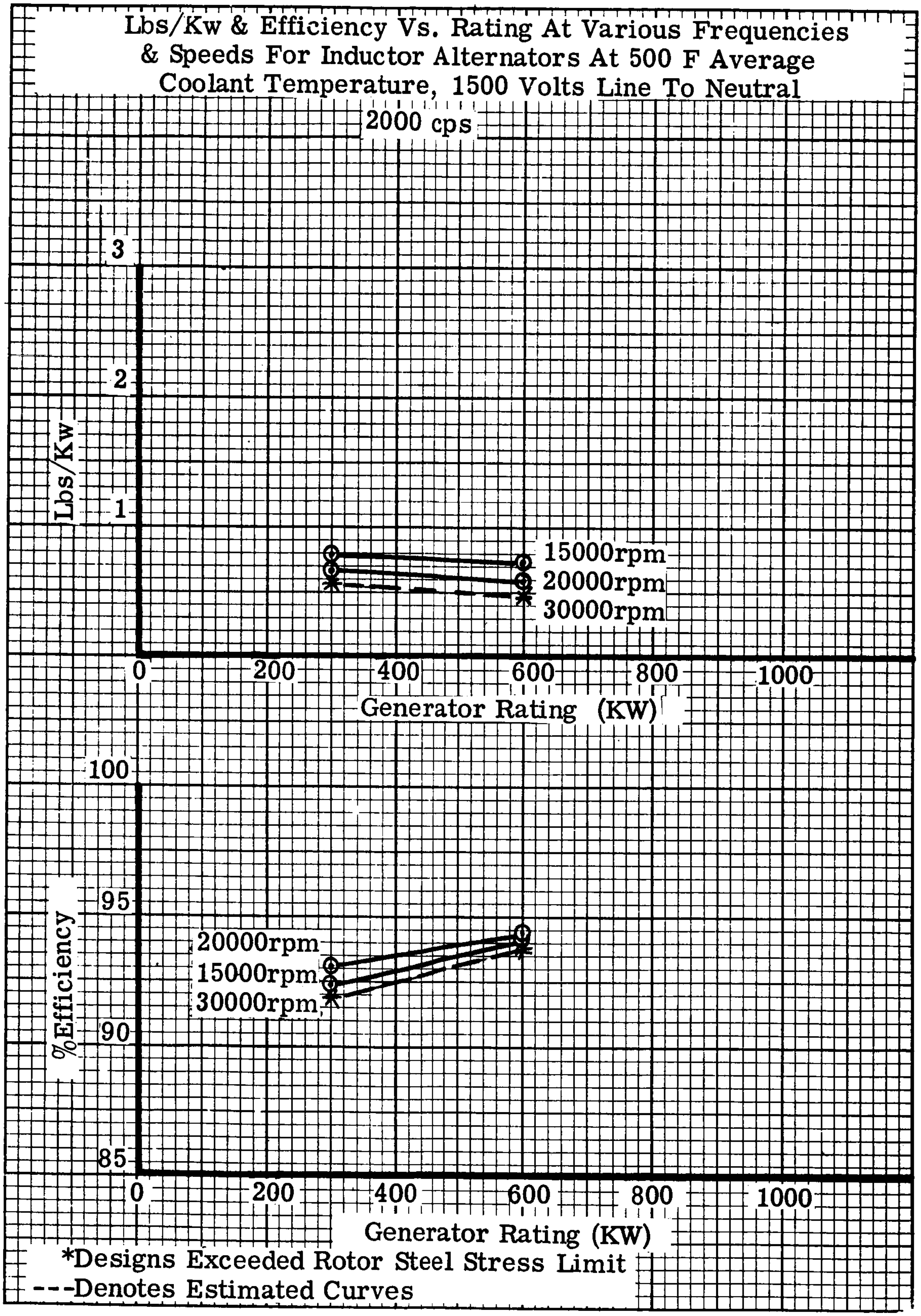

Lbs/Kw & Efficiency Vs. Rating At Various Frequencies
& Speeds For Inductor Alternators At 500 F Average
Coolant Temperature, 1500 Volts Line To Neutral
2000 cps
Lbs/Kw
3
2
1
15000rpm
20000rpm
30000rpm
0
200
400
600
800
1000
Generator Rating (KW)
%Efficiency
100
95
90
85
20000rpm
15000rpm
30000rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 27.

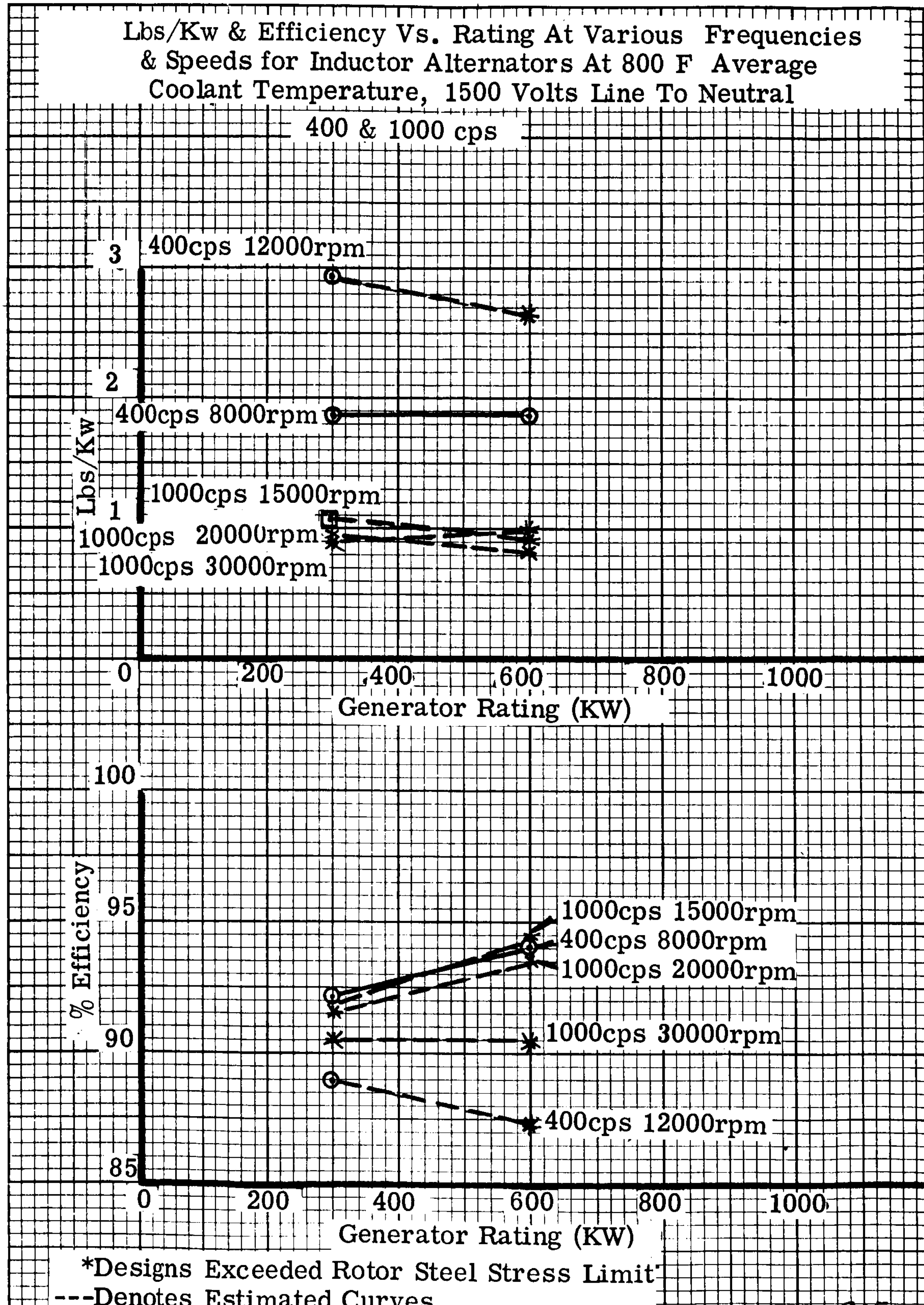
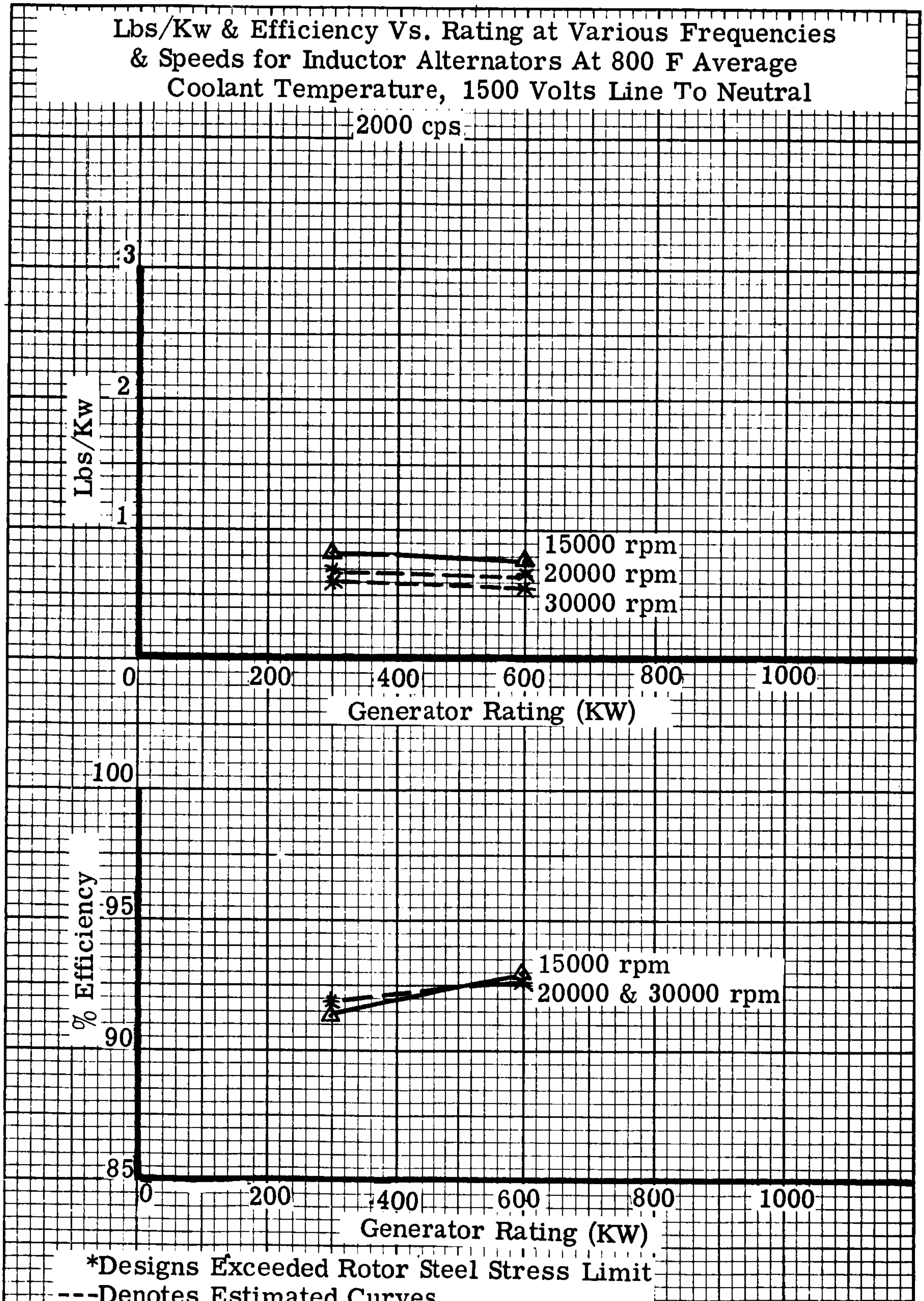

Lbs/Kw & Efficiency Vs. Rating At Various Frequencies & Speeds for Inductor Alternators At 800 F Average Coolant Temperature, 1500 Volts Line To Neutral
400 & 1000 cps
400cps 12000rpm
400cps 8000rpm
1000cps 15000rpm
1000cps 20000rpm
1000cps 30000rpm
Lbs/Kw
3
2
1
0
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
1000cps 15000rpm
400cps 8000rpm
1000cps 20000rpm
1000cps 30000rpm
400cps 12000rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 28.



Lbs/Kw & Efficiency Vs. Rating at Various Frequencies & Speeds for Inductor Alternators At 800 F Average Coolant Temperature, 1500 Volts Line To Neutral
2000 cps
Lbs/Kw
3
2
1
0
15000 rpm
20000 rpm
30000 rpm
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
15000 rpm
20000 & 30000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limit
---Denotes Estimated Curves

Figure 29.

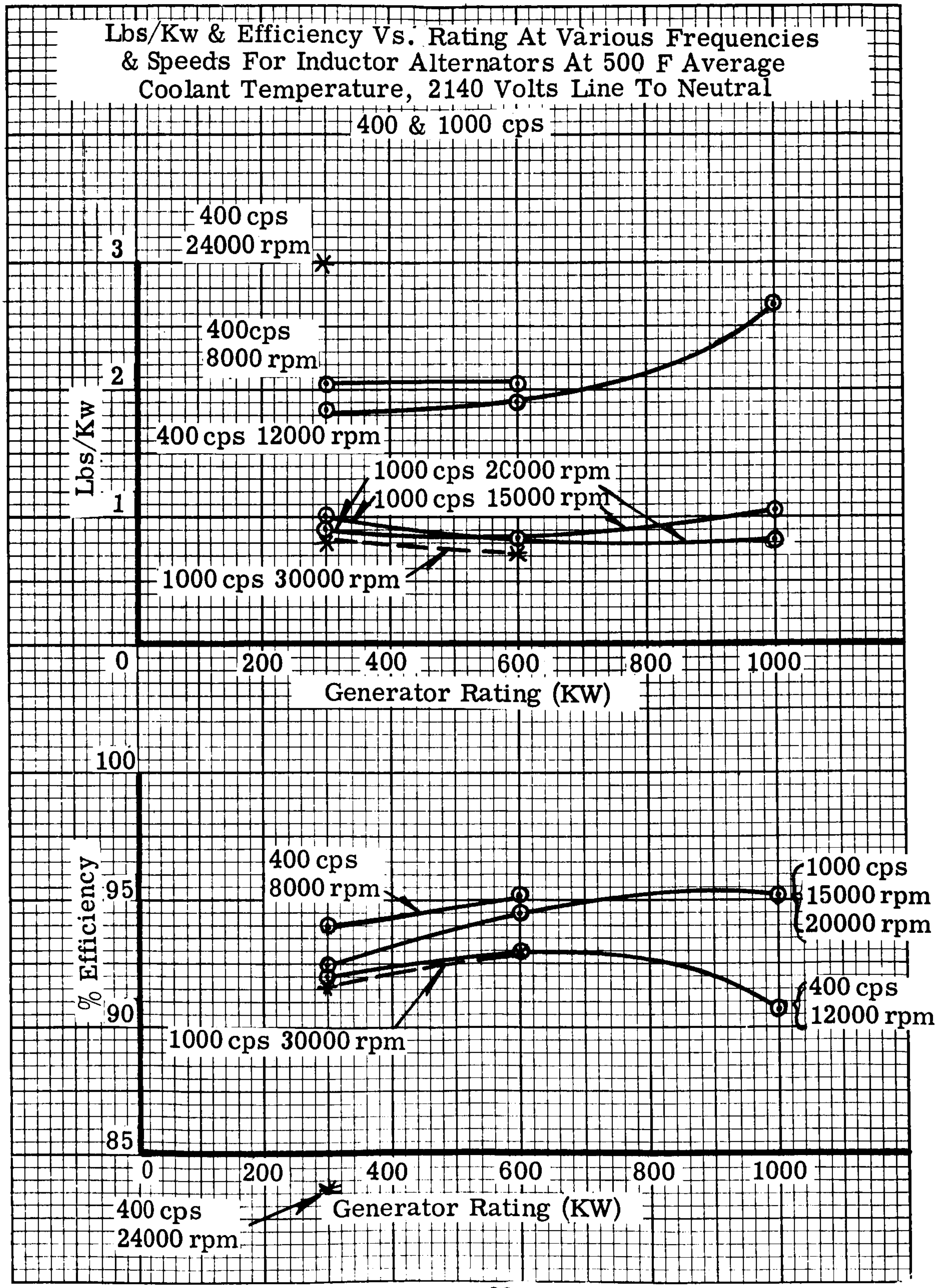
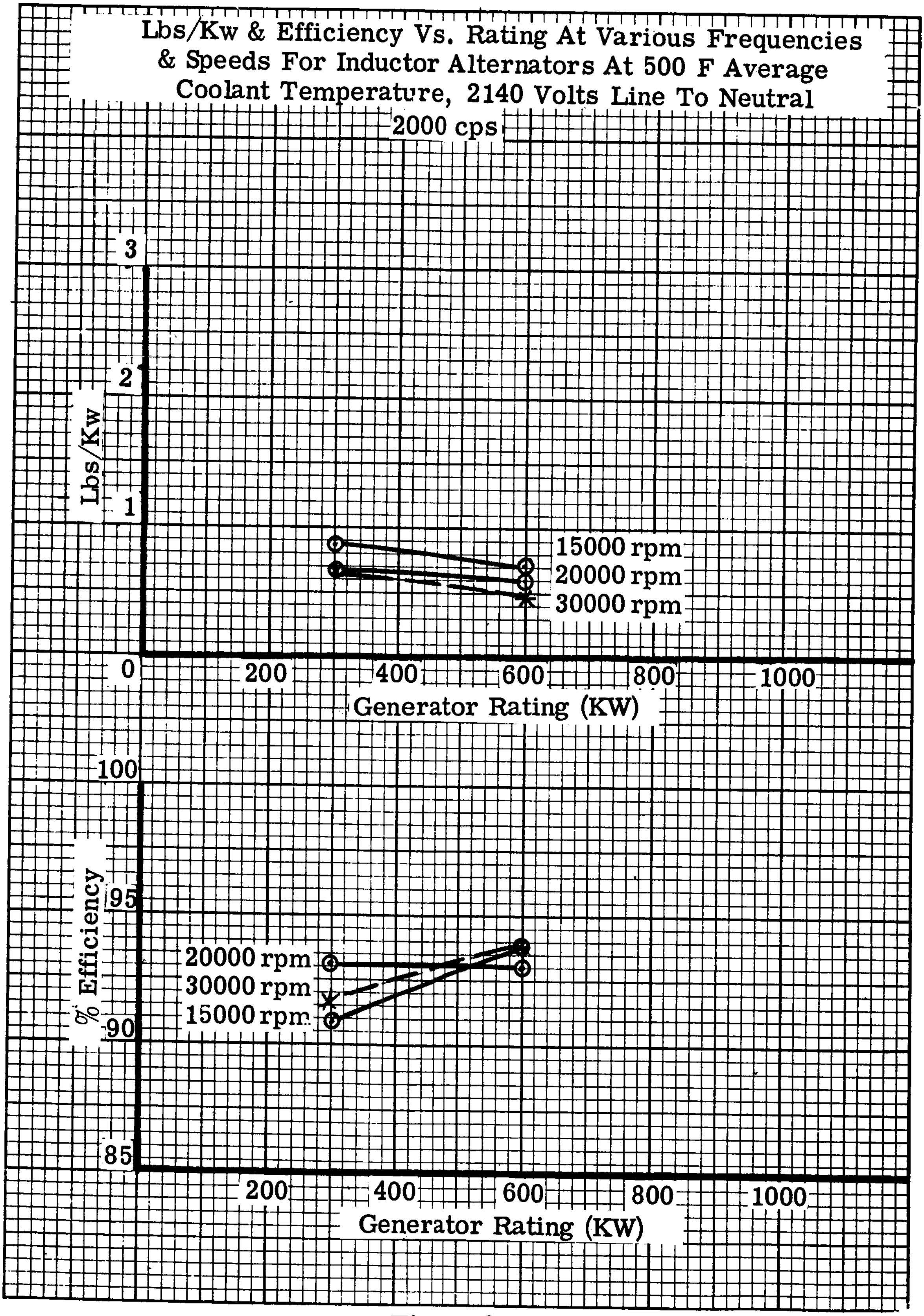
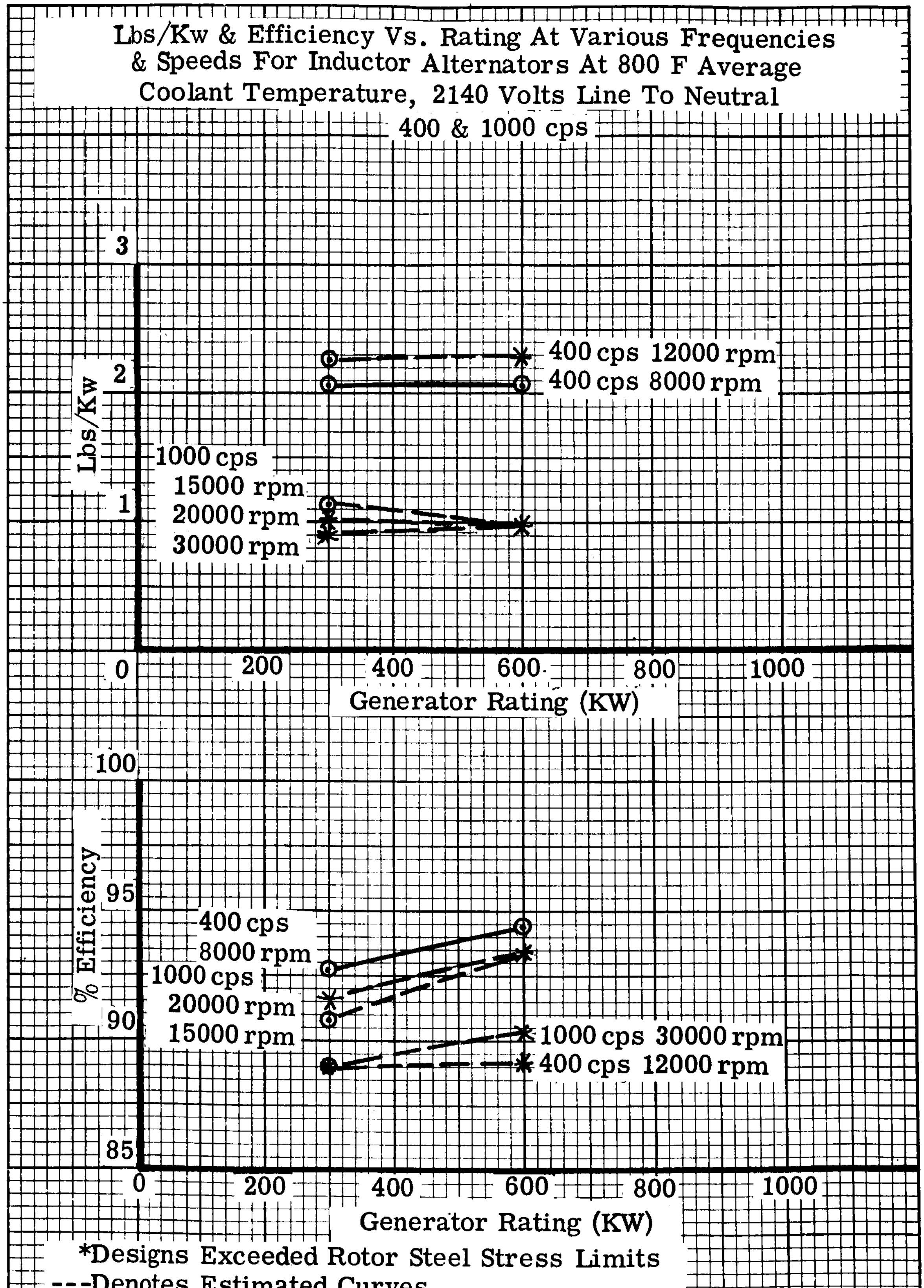

Lbs/Kw & Efficiency Vs. Rating At Various Frequencies
& Speeds For Inductor Alternators At 500 F Average
Coolant Temperature, 2140 Volts Line To Neutral
400 & 1000 cps
400 cps
24000 rpm
400cps
8000 rpm
400 cps 12000 rpm
1000 cps 20000 rpm
1000 cps 15000 rpm
1000 cps 30000 rpm
Lbs/Kw
3
2
1
0
200
400
600
800
1000
Generator Rating (KW)
100
95
90
85
% Efficiency
400 cps
8000 rpm
1000 cps
15000 rpm
20000 rpm
400 cps
12000 rpm
1000 cps 30000 rpm
0
200
400
600
800
1000
400 cps
24000 rpm
Generator Rating (KW)

Figure 30.



Lbs/Kw & Efficiency Vs. Rating At Various Frequencies & Speeds For Inductor Alternators At 500 F Average Coolant Temperature, 2140 Volts Line To Neutral
2000 cps
Lbs/Kw
3
2
1
0
15000 rpm
20000 rpm
30000 rpm
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
20000 rpm
30000 rpm
15000 rpm
200
400
600
800
1000
Generator Rating (KW)

Figure 31.



Lbs/Kw & Efficiency Vs. Rating At Various Frequencies & Speeds For Inductor Alternators At 800 F Average Coolant Temperature, 2140 Volts Line To Neutral
400 & 1000 cps
3
2
1
0
Lbs/Kw
400 cps 12000 rpm
400 cps 8000 rpm
1000 cps
15000 rpm
20000 rpm
30000 rpm
200
400
600
800
1000
Generator Rating (KW)
100
95
90
85
% Efficiency
400 cps
8000 rpm
1000 cps
20000 rpm
15000 rpm
1000 cps 30000 rpm
400 cps 12000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 32.

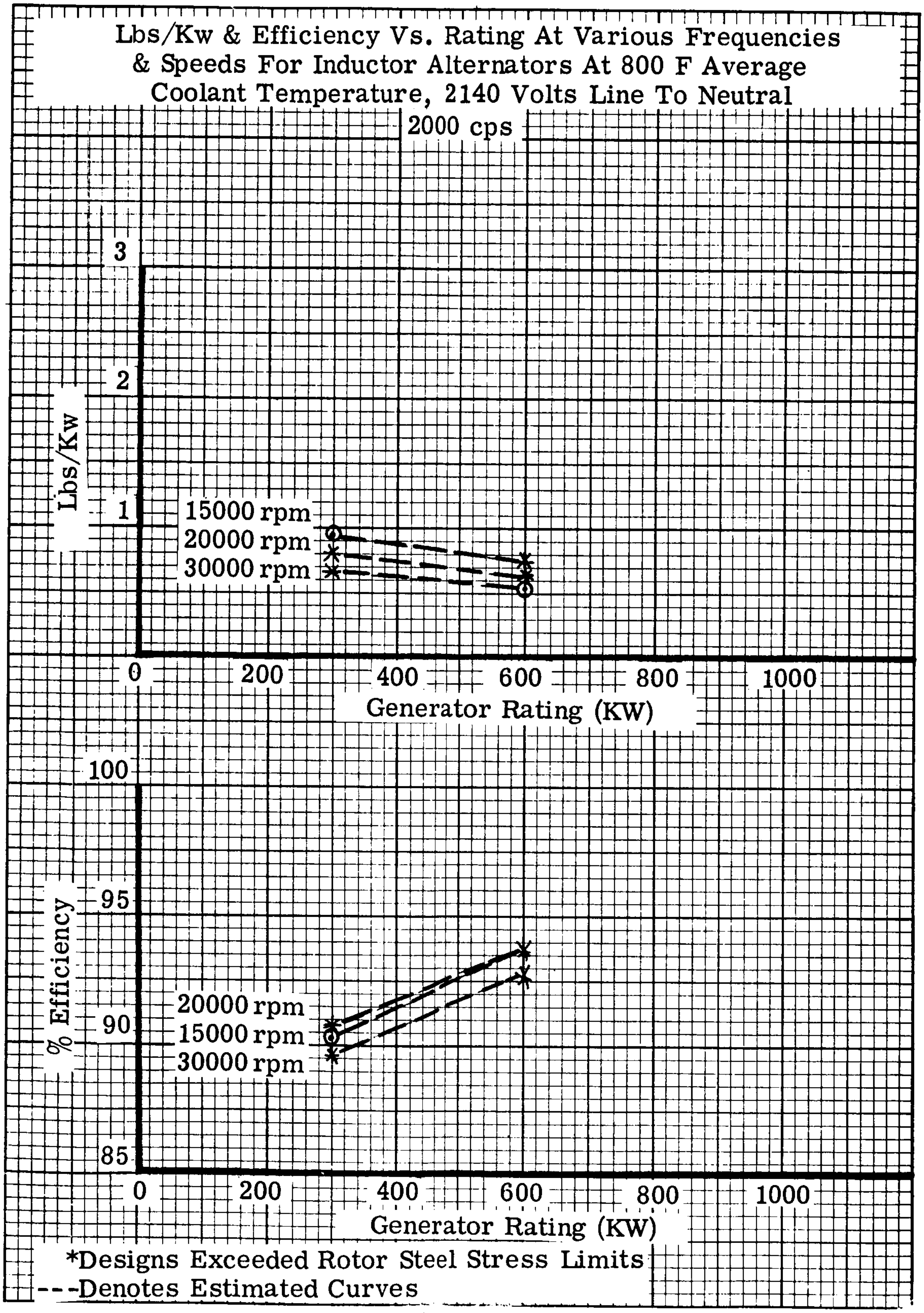

Lbs/Kw & Efficiency Vs. Rating At Various Frequencies & Speeds For Inductor Alternators At 800 F Average Coolant Temperature, 2140 Volts Line To Neutral
2000 cps
Lbs/Kw
3
2
1
15000 rpm
20000 rpm
30000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
% Efficiency
100
95
90
85
20000 rpm
15000 rpm
30000 rpm
0
200
400
600
800
1000
Generator Rating (KW)
*Designs Exceeded Rotor Steel Stress Limits
---Denotes Estimated Curves

Figure 33.

F. MATERIALS LIST

The following materials were used in the design calculations of this study.

Stator Magnetic Material - Hiperco 27

A-C Conductors - Copper

D-C Conductor - Copper

Conductor Insulation - Ceramic

Slot Insulation - Ceramic

Potting Material - Refractory Powder or Glass - Bonded Refractory

Air-Gap Cylinder - Alumina

Stator Interlaminar Insulation - Alkophos

Rotor Steel - SAE 4340, Westinghouse Nivco, or Hiperco 27, depending on rotor stress and temperature

Coolant - Liquid Potassium

A. PARAMETRIC DATA

1. Circuit Selector

The power circuit of the static-exciter, considered in this parametric study, is the three-phase, full-wave, silicon-controlled-rectifier circuit described in section II-B of volume 2. This circuit approach was shown to be lightest in weight and highest in efficiency of all the methods studied.

2. Choice of Parameters

The static-exciter-voltage regulator parametric study is based on the following assumptions:

a. All excitation power can be obtained directly from the generator output terminals and excitation power is required only for load conditions up to rated load.

b. A d-c power supply, external to the excitation system, can be used to flash the generator field winding for generator voltage buildup. Although some switching circuit would be required for this operation, no consideration has been given to this in the parametric study.

c. The basic design, as presented in this study, does not include provisions for paralleling a-c generators. In typical aircraft electric power systems designed for parallel operation of a-c generators, the prime mover contains provisions for dividing real load and the voltage regulator contains provisions for dividing reactive load. Because of the potential difficulty in obtaining satisfactory real load division with turbine drives, it appears that paralleling could be best accomplished at the d-c bus rather than the a-c bus. Provisions for paralleling could then be satisfactorily provided by the voltage regulator.

d. A two to one safety factor is used on the voltage ratings of the controlled rectifiers and conventional rectifiers in the power amplifier. This derating provides greater reliability and allows safe operation during generator voltage transients.

e. Electrical component weights are based upon a rated generator terminal voltage of 1500 volts. For a rated generator voltage of 2140 volts there will be an approximate 3 percent increase in weight; and for a rated generator voltage of 1000 volts there will be an approximate 3 percent decrease in weight.

Parametric data is shown as a function of the rated output power of the static exciter-voltage regulator. The range of output power considered was 2 kw to 6 kw.

The curves presented are based upon calculations at both the 3 kw and the 6 kw level with other points obtained by extrapolation of the calculated data.

The exciter-regulator power loss versus the exciter-regulator rating is shown on Figure 34.

3. Cooling and Packaging Considerations

The proposed regulator packages are to be formed from aluminum sheet metal for low weight and high thermal conductivity. Cooling is accomplished by conducting losses from electrical components to a cold plate. The cold-plate design is formed aluminum sheet metal with coolant tubes or ducts welded or brazed along the length and bottom of the package base. All of the regulator designs proposed are bolted down with four mounting points.

Calculations of package weights and required coolant flow were based on the following assumptions:

a. Conduction is the primary means of cooling.

b. Turbulent flow is assumed for all 6-kw, 170F-coolant regulators. Laminar flow is assumed for all other design cases.

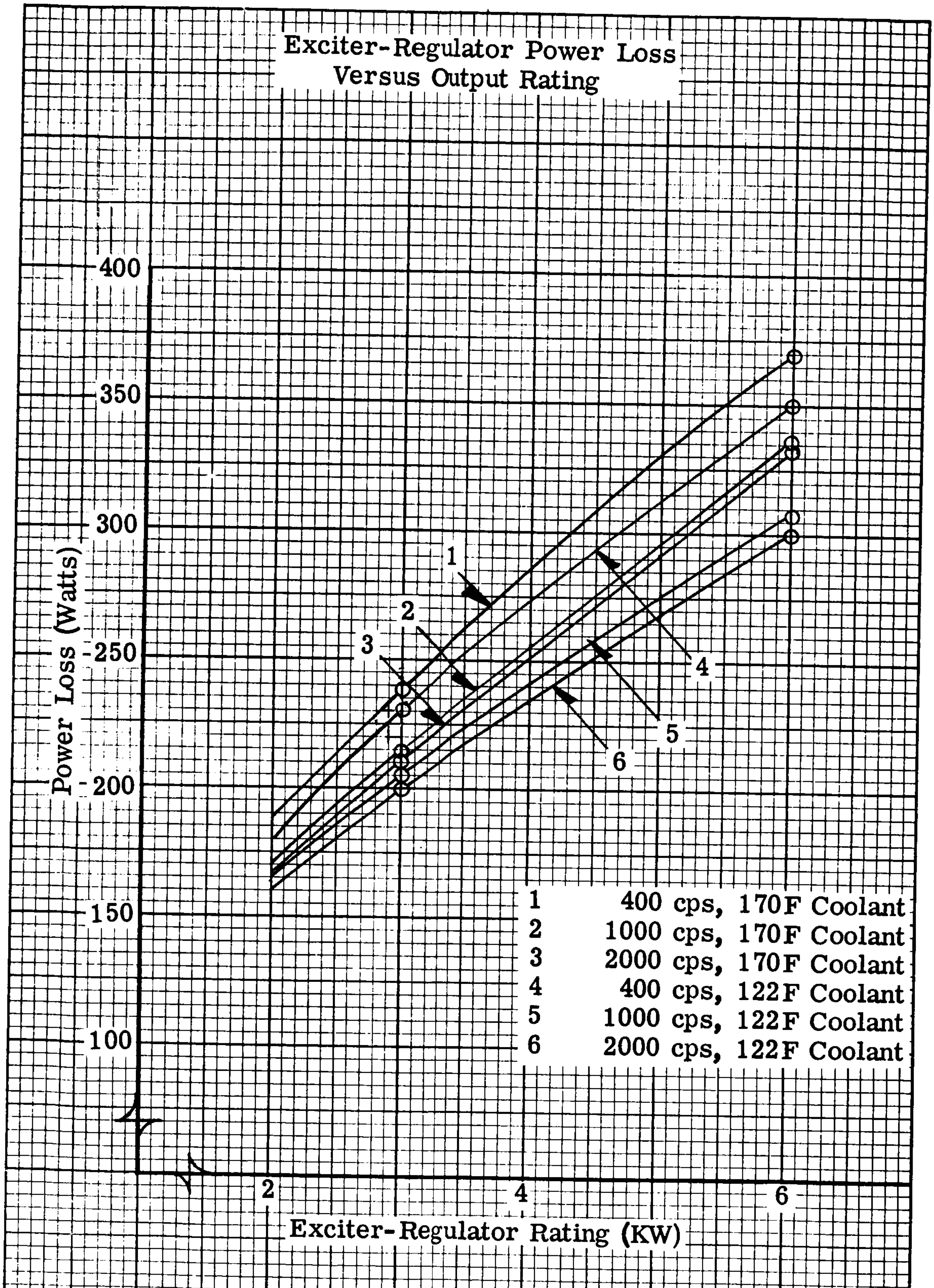
c. Beryllium oxide is the insulation for all controlled rectifiers. The thermal resistance assumed is 0.4C per watt from the rectifier case to the cold plate.

d. The liquid coolant chosen for this study is monoisopropyl biphenyl (MIPB). See section III, volume 1, for properties.

e. The average coolant temperatures studied were 122F and 170F.

f. k The junction temperature of controlled rectifiers is limited to 94C (201F), which is 25 percent below the maximum junction temperature, 125C, specified by the manufacturer.

g. The hot spot temperature of the magnetic amplifiers is limited to 255F and that of the transformers to 390F.



Exciter-Regulator Power Loss
Versus Output Rating
400
350
300
250
200
150
100
Power Loss (Watts)
1
2
3
4
5
6
1 400 cps, 170F Coolant
2 1000 cps, 170F Coolant
3 2000 cps, 170F Coolant
4 400 cps, 122F Coolant
5 1000 cps, 122F Coolant
6 2000 cps, 122F Coolant
2
4
6
Exciter-Regulator Rating (KW)

Figure 34.

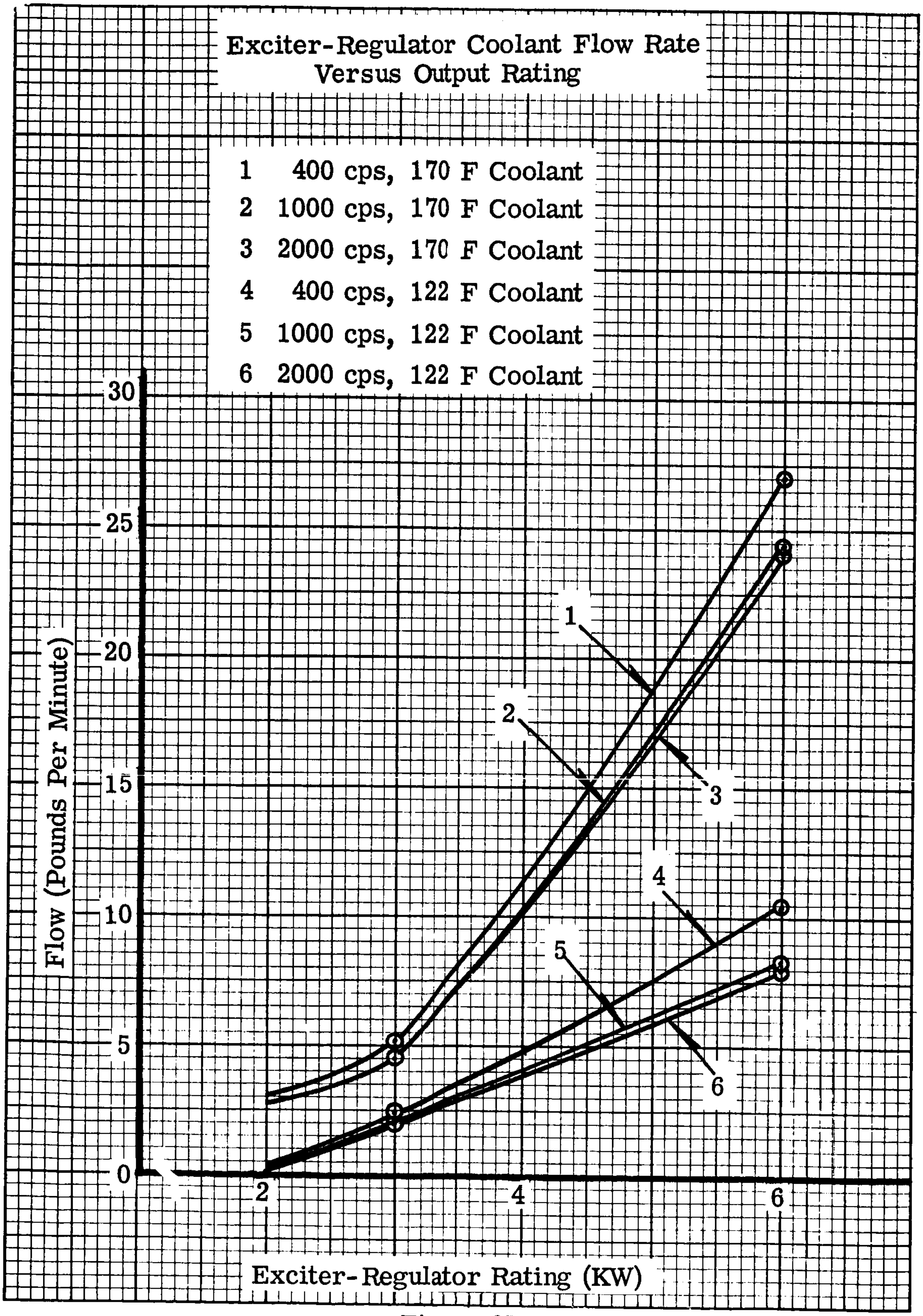
The mass flow values (pounds per minute of MIPB), given in Figure 35, are based upon maximum allowable temperature rises permitted after all component hot spot or junction temperatures have been determined, and all thermal resistances added. Therefore, the mass flow value given in Figure 35 represents the minimum flow required to maintain the derated hot spot or junction temperatures chosen.

For those regulators where a high maximum-allowable-temperature rise was permitted, laminar flow was assumed to achieve minimum flow rates. For those regulators where the maximum allowable temperature rise was small, turbulent flow and higher flow rates of MIPB were required for cooling.

The exciter-regulator package weight versus the exciter-regulator output rating is shown on Figure 36.

3. Parametric Data Utilization

With the parametric data presented in this section, it is possible to determine an appropriate exciter-regulator loss, coolant flow, and weight for all but two of the 108 generator designs presented.



Exciter-Regulator Coolant Flow Rate Versus Output Rating
1 400 cps, 170 F Coolant
2 1000 cps, 170 F Coolant
3 2000 cps, 170 F Coolant
4 400 cps, 122 F Coolant
5 1000 cps, 122 F Coolant
6 2000 cps, 122 F Coolant
Flow (Pounds Per Minute)
0
5
10
15
20
25
30
2
4
6
Exciter-Regulator Rating (KW)
1
2
3
4
5
6

Figure 35.

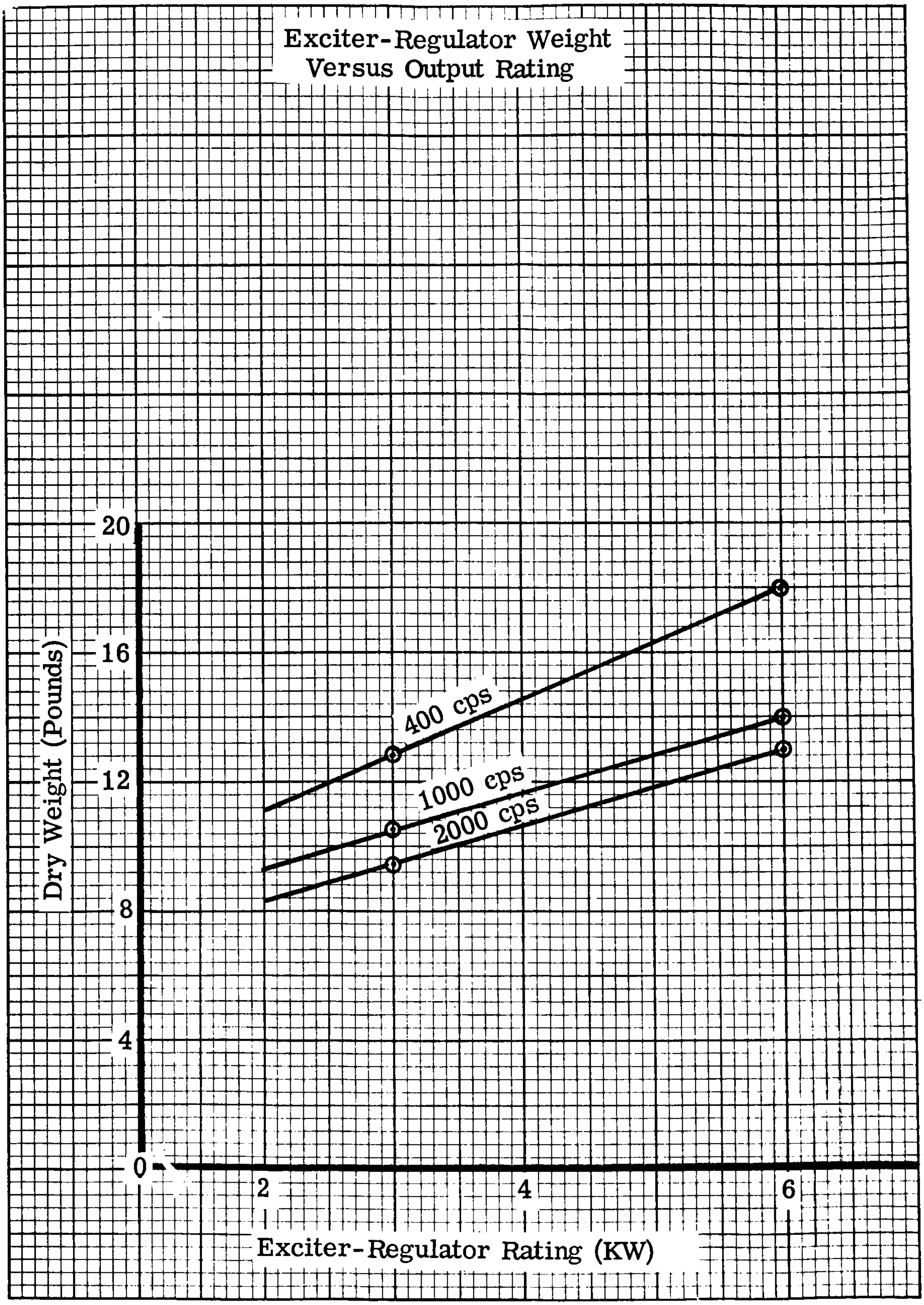

Exciter-Regulator Weight
Versus Output Rating
Dry Weight (Pounds)
20
16
12
8
4
0
400 cps
1000 cps
2000 cps
2
4
6
Exciter-Regulator Rating (KW)

Figure 36.

B. LIST OF MATERIALS AND COMPONENTS

The following would be used in the fabrication of the static exciter-voltage regulators.

1. Electrical Components

   a. Silicon controlled rectifiers (Jedec Type 2N1799, Westinghouse Electric; Type 2N2030 or 2N689, General Electric)

   b. Silicon rectifiers (Jedec Type 1N1402 or 1N1197; Westinghouse Electric; Type 1N645, Texas Instruments; Type 1N746A, Motorola)

   c. Wirewound resistors - typical suppliers: (1) Tepro Electric type TS, (2) Dale Electronics, type WW, (3) Sage Electronics, type S.

   d. Wirewound and encapsulated potentiometers (Clarostat Mfg. Co., Cat. CM25764).

   e. Compressed mica paper capacitor impregnated with thermal setting polyester. (Bendix Corp., Cat. No. RM70B-1AC250K).

   f. Saturable reactors

      (1) Core material: 80% nickel-iron alloy, toroidal tape wound core encased with silicone grease in an aluminum core box. (Typical supplier: G. L. Electronics. Material trade name: Hymu-80).

      (2) Magnet wire: ML insulated copper wire.

      (3) Insulation: Mylar tape.

   g. Transformers

      (1) Core material: grain oriented silicon steel (Typical supplier: Westinghouse Electric. Material trade name: Hipersil).

      (2) Magnet wire: ML insulated copper wire.

   h. Hookup wire - Teflon insulated copper wire.

2. Packaging Materials

   a. Aluminum QQ-A-318 Cond. 1/2 H

b. Clips, Component - Cadmium Plated Steel MIL-S-17919.

c. Solder, Tin Lead 60-40

d. Epoxy 100% Solid

e. Epoxy 53841GD Blue Thixotropic epoxy resin fluidized powder.

f. Silicone Rubber

g. Glass Filled Epoxy Nema G-10.

h. Beryllium Oxide

i. Extruded Teflon

j. Steel QQ-S-633-FS1010

k. Carbon Steel QQ-S-633 C1137

l. Clear Phenolic Varnish, Vacuum pressure impregnated

m. Teflon Impregnated Glass Cloth

n. Silicone Micarta Nema G-7

o. 8468-2 Tape Thermosetting Glass Tape

p. Varnish, Silicone D. C. 997

q. Nickel Plating

r. Gold Plating

A. PARAMETRIC DATA

1. Electrical Considerations

To show how losses vary with weight, a number of transformer designs were made for each operating condition. The total weight was then determined for each design. The total weight and the losses are plotted in Figures 37, 38, 39, and 40 for 250 kw at 500F, 500 kw at 500F, 250 kw at 800F, and 500 kw at 800F, respectively. The losses for 500F coolant are based on a copper and iron temperature of 575F and the losses at 800F coolant are based on a copper and iron temperature of 925F. The curves also show the effect of frequency on weights and losses.

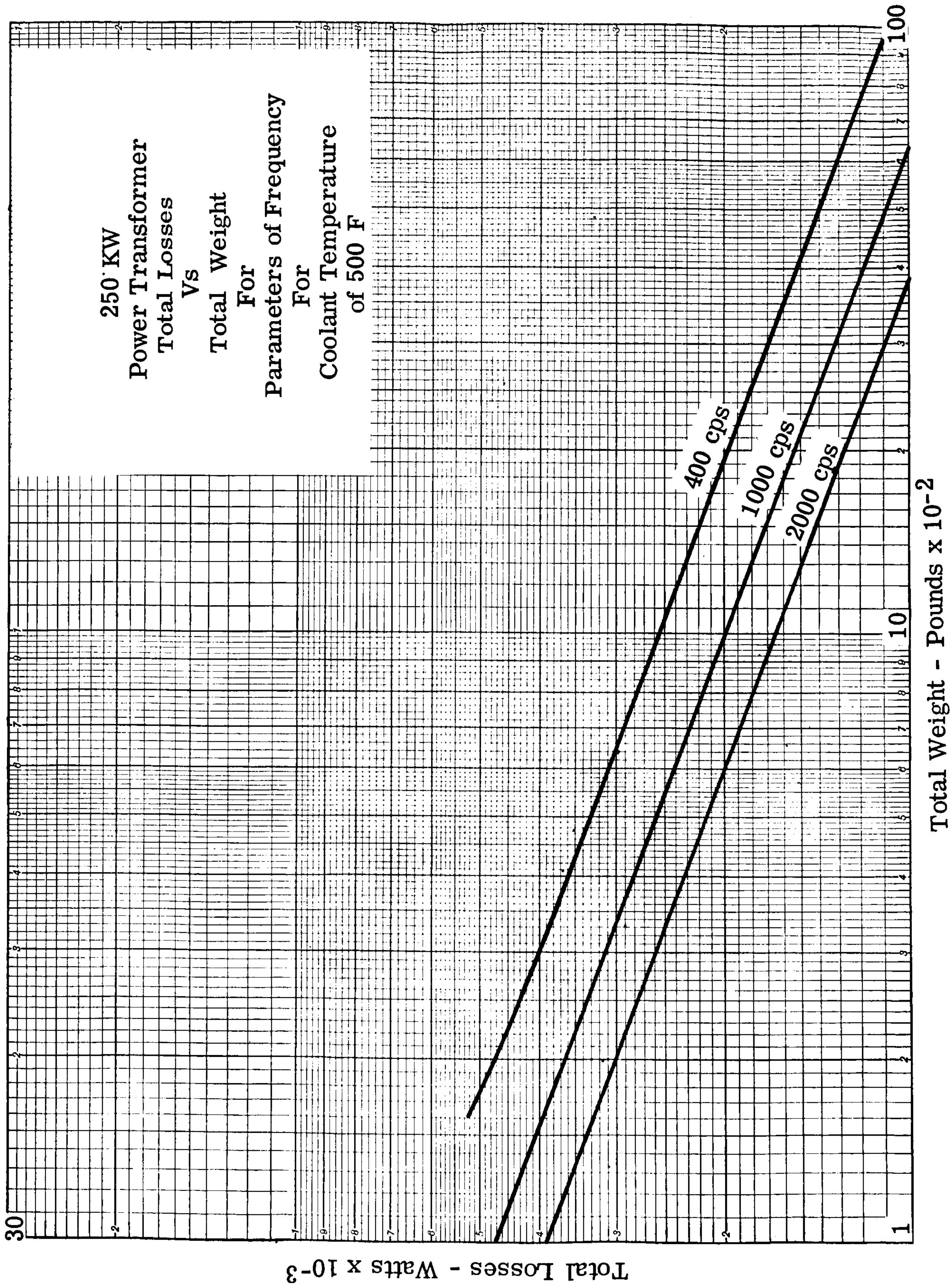
In the transformer designs the following assumptions were made as a basis for the calculations: (1) The copper had 100 percent conductivity at the temperature at which the losses were calculated; (2) Because data showing temperature effect on magnetic materials was not available at frequencies above 400 cps, it was assumed that the temperature effect would be similar for the higher frequencies. Available data was then projected to give working values. (3) So that higher cooling efficiency might be realized, a tape-wound core with an inorganic binder was assumed. Inorganic binders for tape-wound cores to temperatures of 1100F are under development at the present time; and appear to be feasible.

2. Cooling and Packaging Considerations

All parametric cooling data is based upon the use of eutectic NaK coolant fluid. Eutectic NaK exhibits excellent properties for both the 500F and 800F designs. The one-to-ten-megawatt study indicated that the small convection film temperature drop of NaK would yield a lighter overall cooling system design.

For most effective cooling, the coolant must be passed directly through the transformers. This will be accomplished by placing insulated, stainless-steel ducts between the primary and secondary windings of the transformer and between the core and primary windings. The coolant flow will be parallel in all ducts at an assumed velocity of one foot/second. Based upon this cooling configuration and constant velocity flow for all designs, the flow rate of coolant is directly dependent upon the transformer size and losses. The transformer, hot-spot temperatures is limited to 750F and 1100F for the 500F and 800F coolants, respectively. Using the above conditions, the coolant flow rate for each transformer was calculated.

The total packaged weight of any transformer is the summation of the electro-magnetic weight, the insulation and mounting hardware weight,



250 KW
Power Transformer
Total Losses
Vs
Total Weight
For
Parameters of Frequency
For
Coolant Temperature
of 500 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds x 10^{-2}
Total Losses - Watts x 10^{-3}
100
10
1
30

Figure 37.

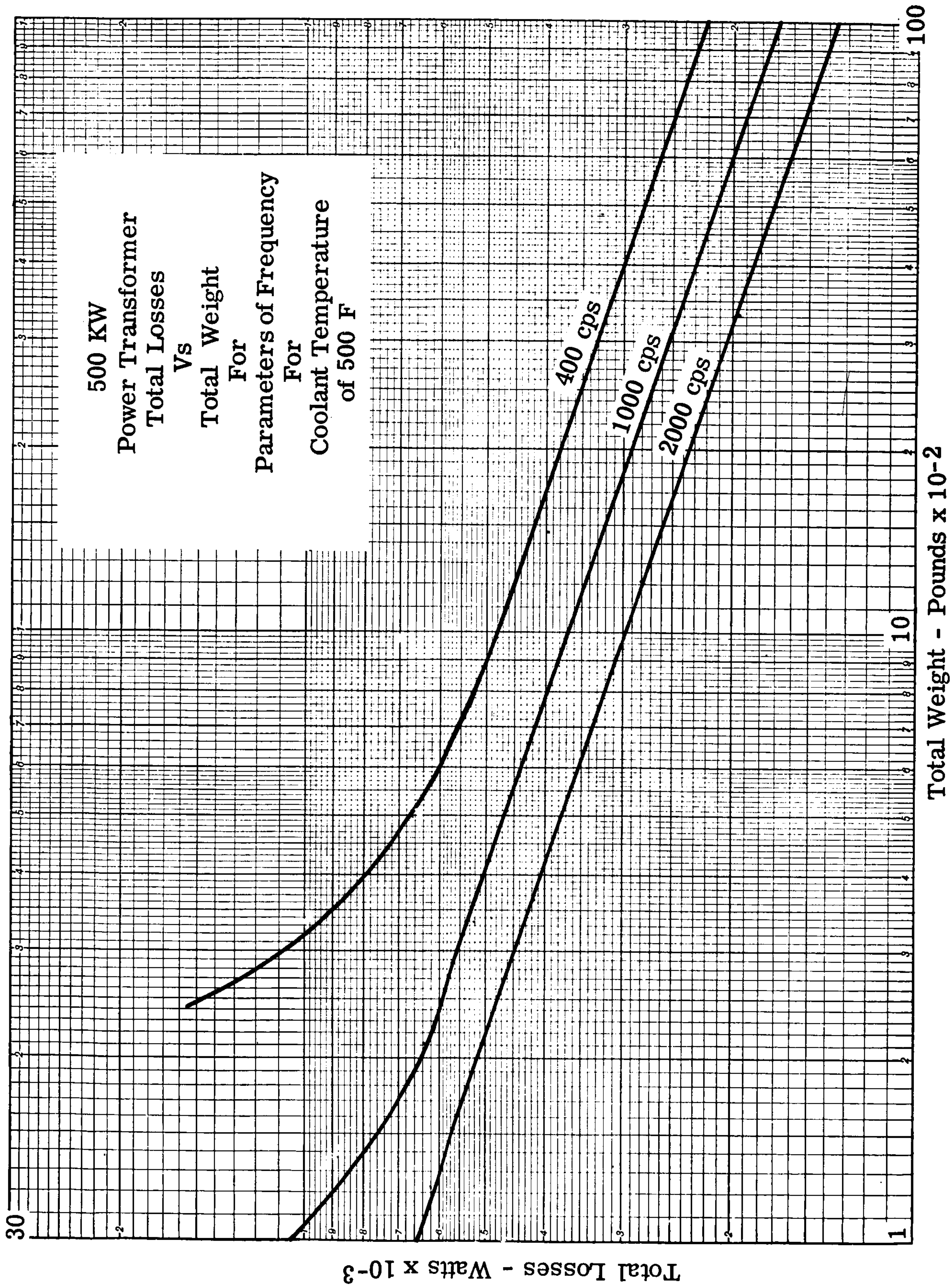
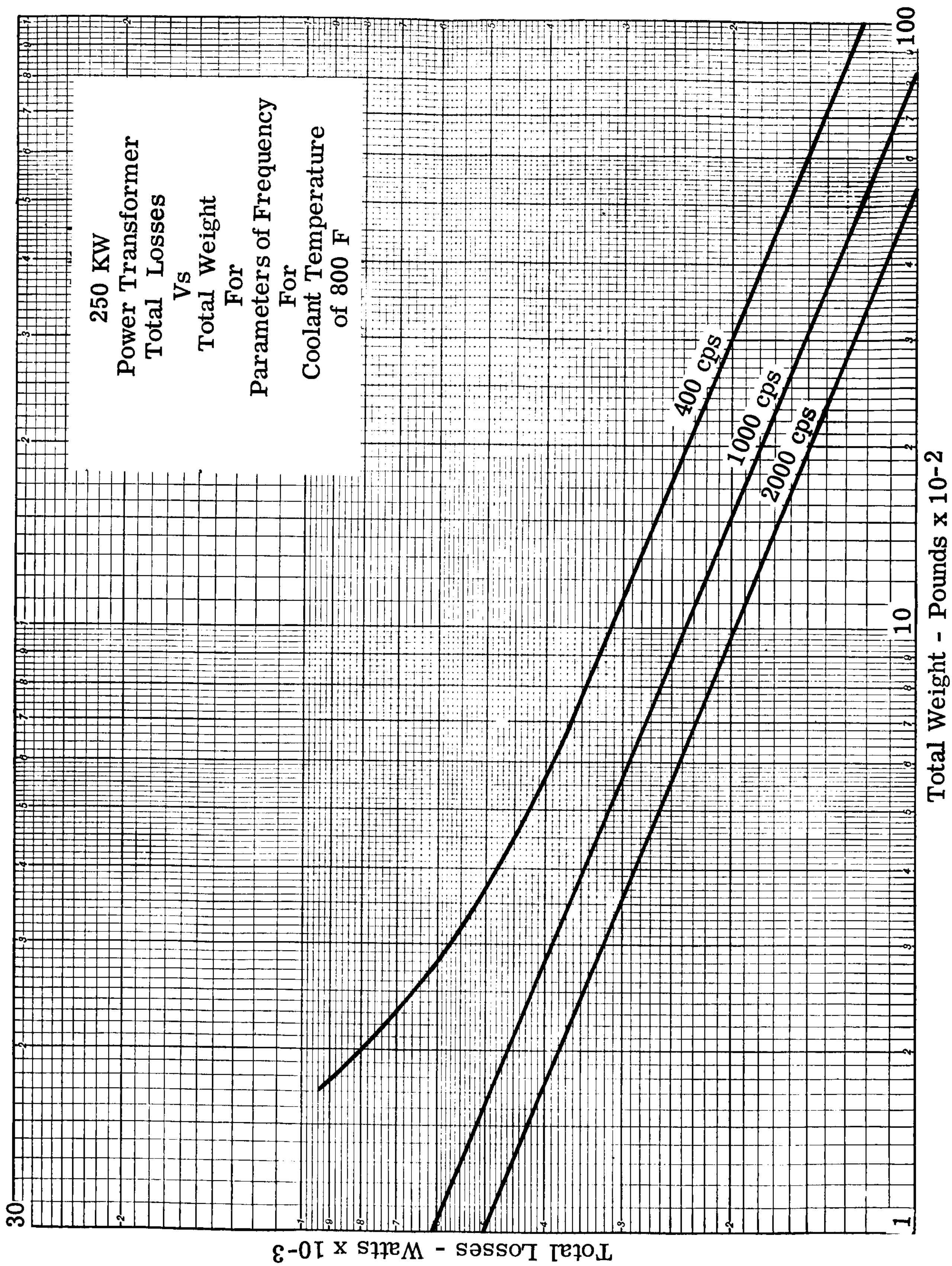

500 KW
Power Transformer
Total Losses
Vs
Total Weight
For
Parameters of Frequency
For
Coolant Temperature
of 500 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds x 10-2
Total Losses - Watts x 10-3
30
1
10
100

Figure 38.



250 KW
Power Transformer
Total Losses
Vs
Total Weight
For
Parameters of Frequency
For
Coolant Temperature
of 800 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds x 10-2
Total Losses - Watts x 10-3
1
10
100
30

Figure 39.

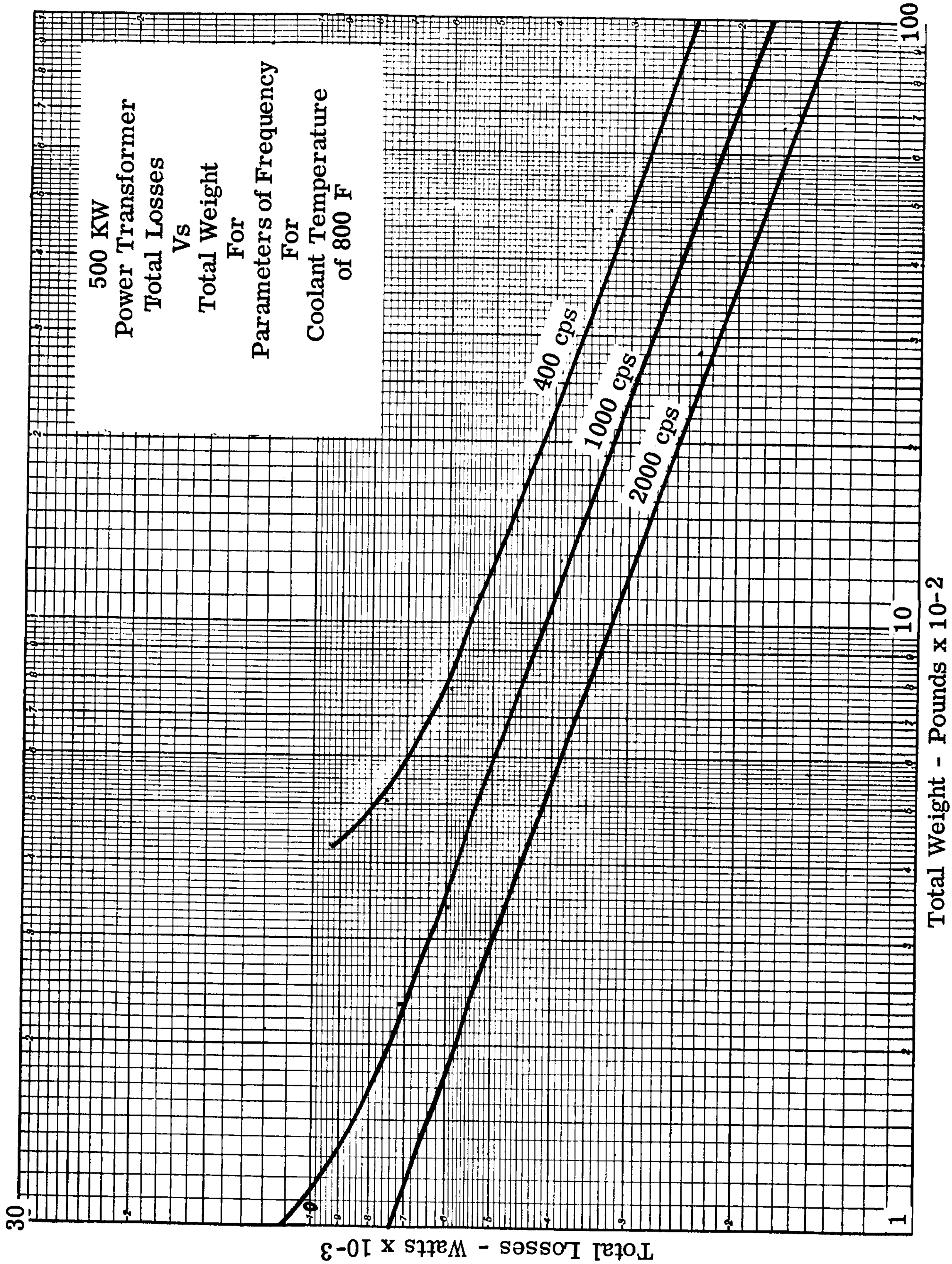

500 KW
Power Transformer
Total Losses
Vs
Total Weight
For
Parameters of Frequency
For
Coolant Temperature
of 800 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds x 10-2
Total Losses - Watts x 10-3
1
10
100
30

Figure 40.

and the cooling system weight. The insulation and mounting hardware weight were found to be approximately 42 percent of the electro-magnetic weight for all 1000 volt designs. Cooling system weight was found to be virtually proportional to transformer heat loss. Therefore, the percentage of total weight comprised by the cooling system was found to vary from 0.5 percent to 4 percent, depending on the magnitude of the losses in each case.

Figures 41, 42, 43, and 44 show cooling flow variation with weight. These curves show that for the heavier designs a large increase in weight is accompanied by only a small decrease in fluid flow. To select a transformer weight for a specific power, temperature, and frequency condition, the weight of the external cooling system must be considered.

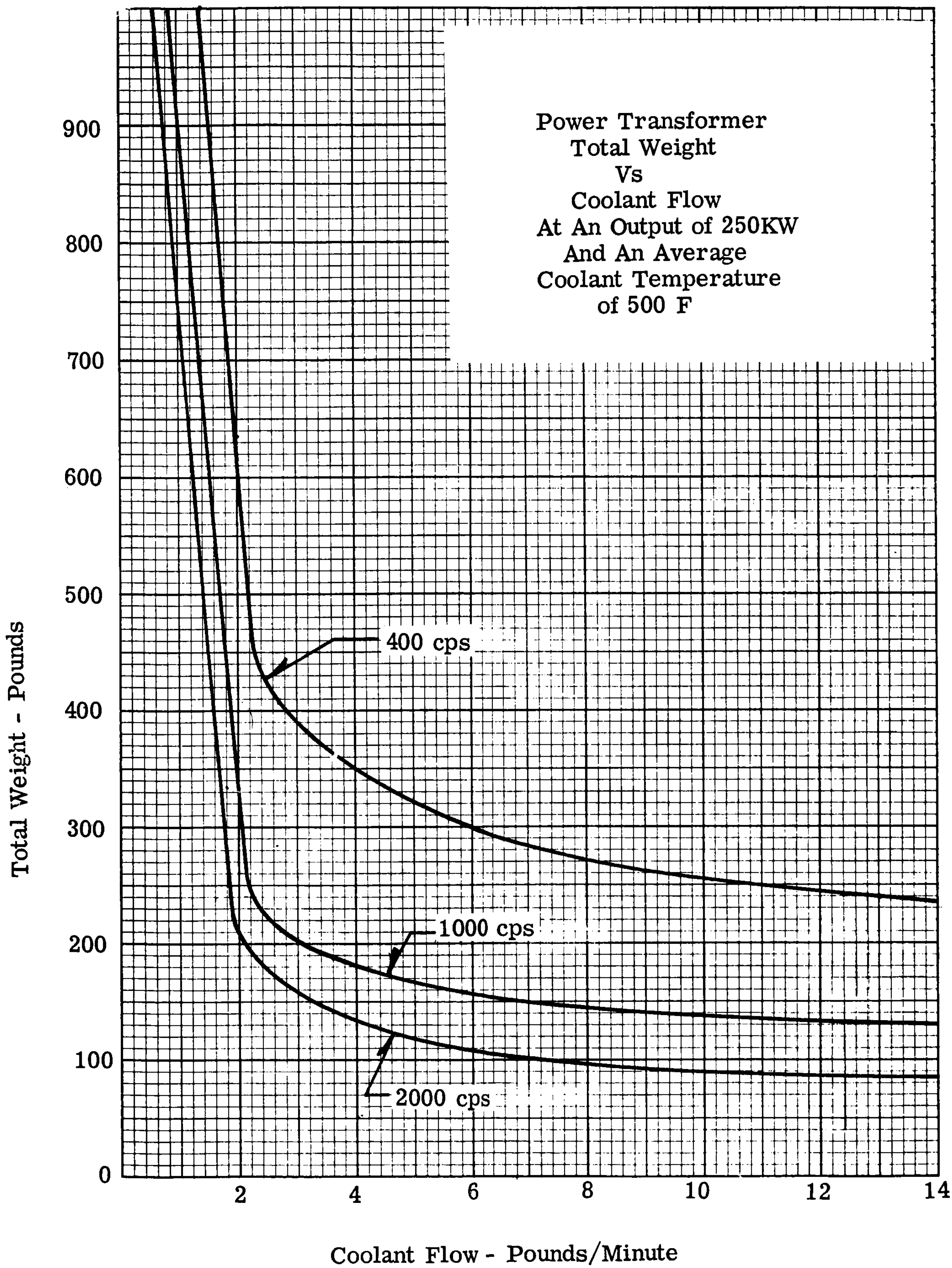

Power Transformer
Total Weight
Vs
Coolant Flow
At An Output of 250KW
And An Average
Coolant Temperature
of 500 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds
0
100
200
300
400
500
600
700
800
900
2
4
6
8
10
12
14
Coolant Flow - Pounds/Minute

Figure 41.

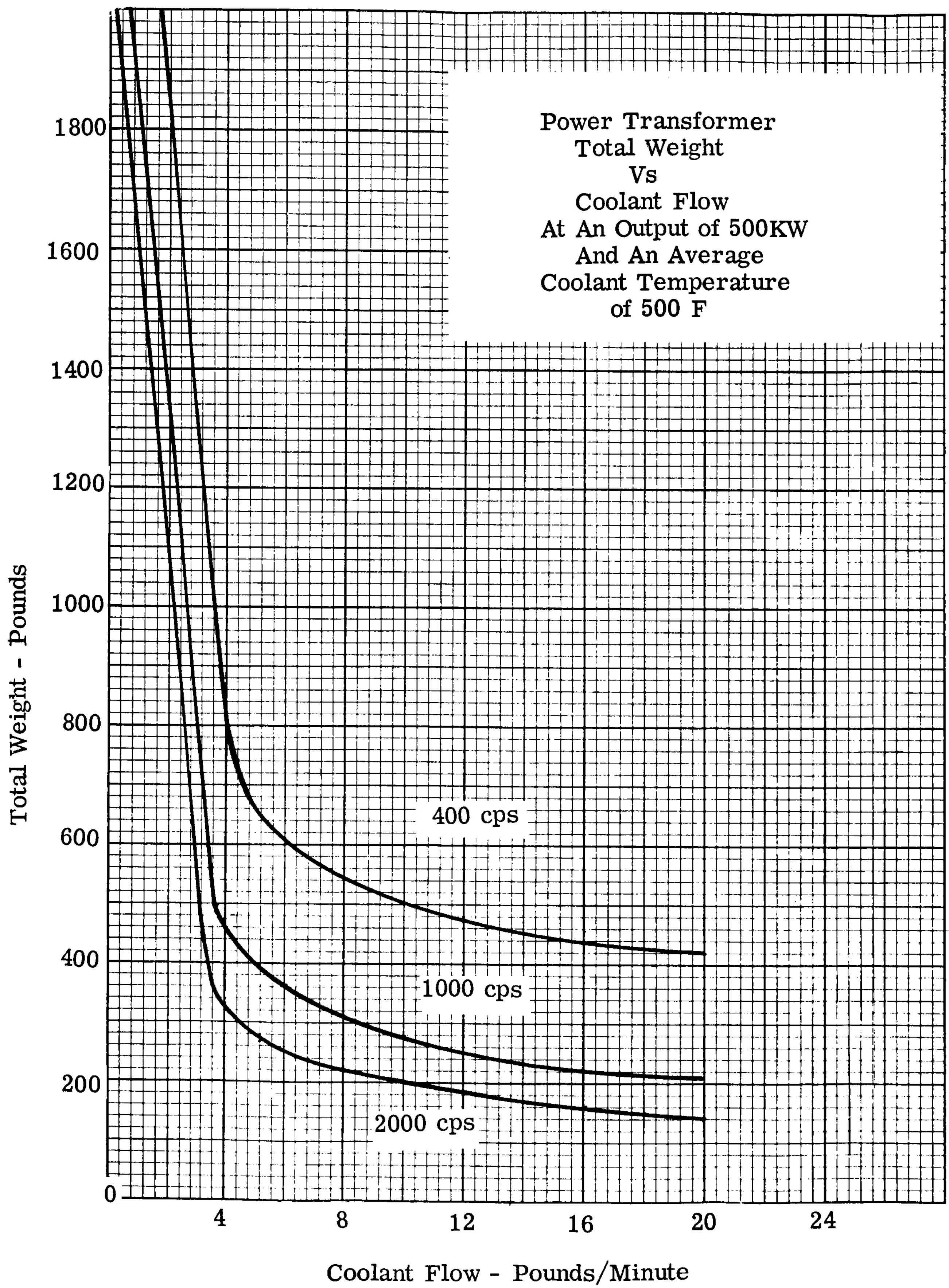

Power Transformer
Total Weight
Vs
Coolant Flow
At An Output of 500KW
And An Average
Coolant Temperature
of 500 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds
1800
1600
1400
1200
1000
800
600
400
200
0
4
8
12
16
20
24
Coolant Flow - Pounds/Minute

Figure 42.

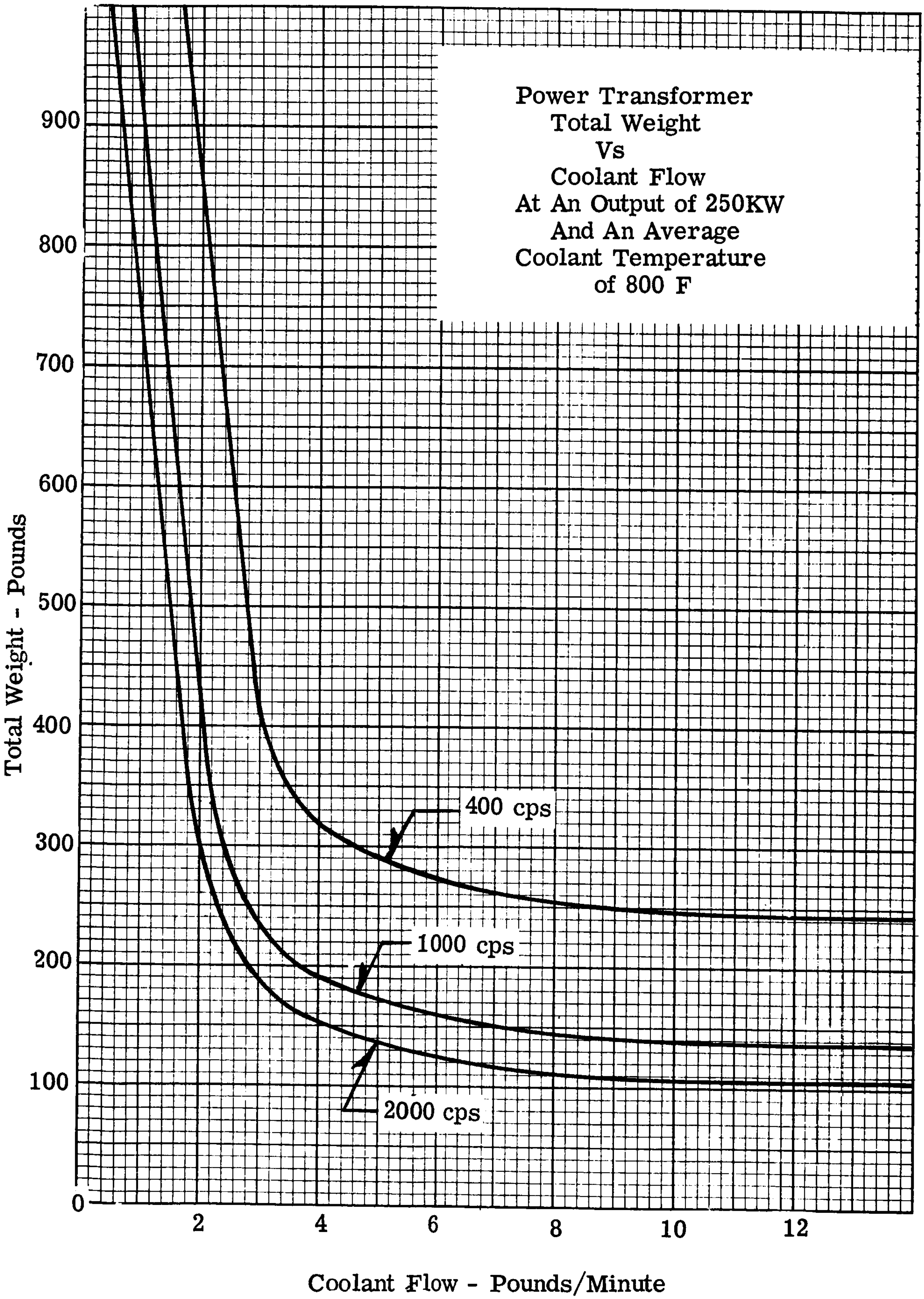

Power Transformer
Total Weight
Vs
Coolant Flow
At An Output of 250KW
And An Average
Coolant Temperature
of 800 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds
900
800
700
600
500
400
300
200
100
0
2
4
6
8
10
12
Coolant Flow - Pounds/Minute

Figure 43.

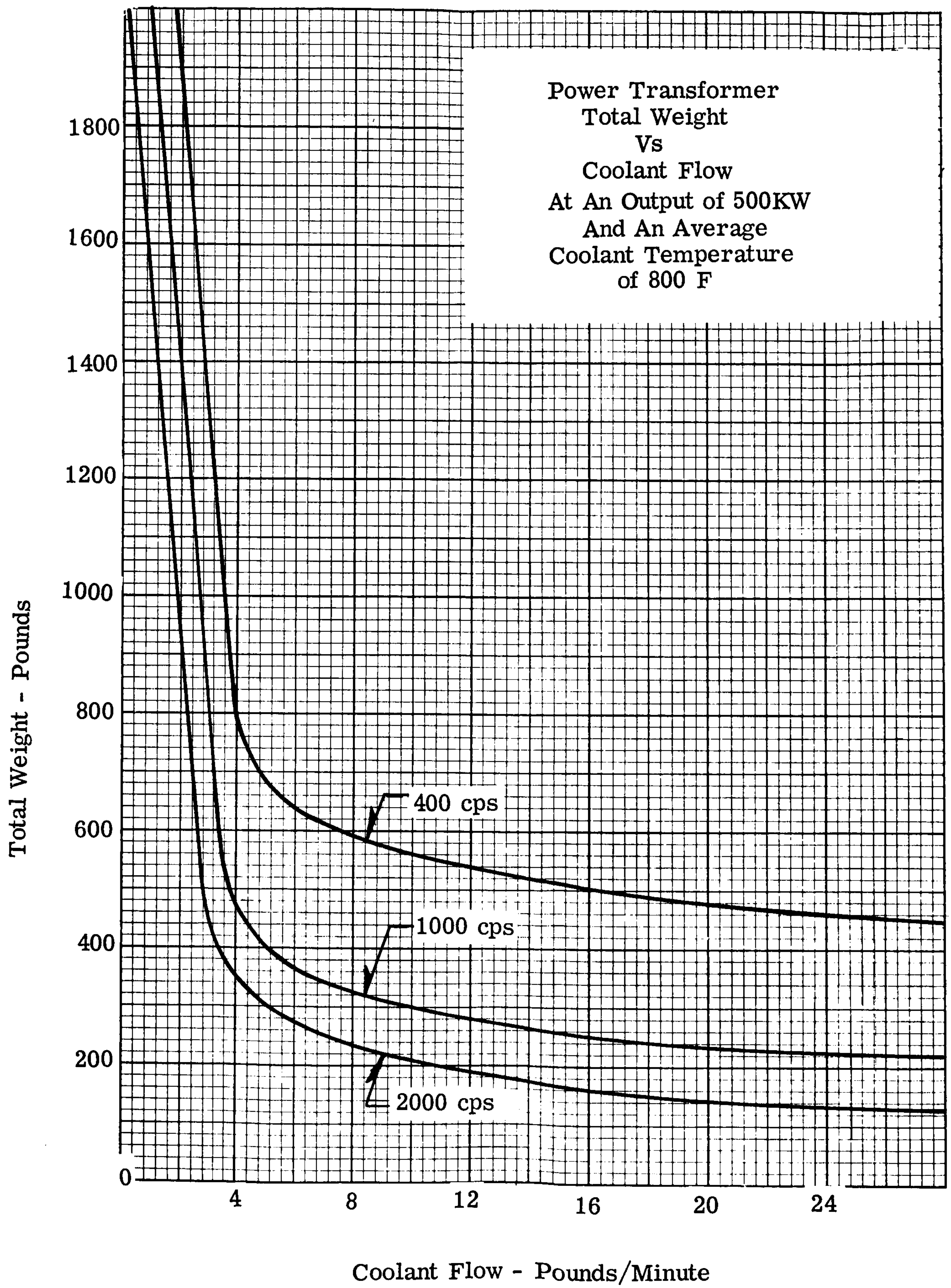

Power Transformer
Total Weight
Vs
Coolant Flow
At An Output of 500KW
And An Average
Coolant Temperature
of 800 F
400 cps
1000 cps
2000 cps
Total Weight - Pounds
Coolant Flow - Pounds/Minute
0
200
400
600
800
1000
1200
1400
1600
1800
4
8
12
16
20
24

Figure 44.

B. LIST OF MATERIALS

1.	Coolant	Eutectic NaK
2.	Coolant Tubes	Type 321 Stainless or Type 316 (extra low carbon) Steel
3.	Heat Sink	Copper
4.	Supporting Structure	High strength austenitic steel or a stable stainless steel (Type 321)
5.	Hardware	High strength austenitic steel or a stable stainless steel (321)
6.	Cooling Tube Insulation	Mica
7.	Conductor	Copper
8.	Core	Silicon Steel
9.	Insulation	Mica, glass, asbestos, and combinations of the preceding

A. RECTIFIER PARAMETRIC DATA

1. Electrical Considerations

The basic transformation circuit considered in the rectifier circuit parametric study is the Wye, 6-phase, Delta, Double Way (Bridge). This configuration provides an overall rectifier system with the least number of diodes and highest rectifier efficiency. The electrical operation of this circuit is described in section III-A of volume 2. This part of the study considers the diodes and voltage balancing components.

Table 8 lists the component quantity, size, weight, and power losses for a single-bank, silicon-diode system capable of providing 250 kw and 500 kw at a direct current output voltage of 5 kilovolts for three input frequencies of 400, 1000, and 2000 cycles per second.

To calculate the data for Table 8 several assumptions were made to facilitate the comparison of this data with the data presented in Section III of volume 2.

a. The number of diodes per rectifier bridge were determined by requiring the diode peak-inverse-voltage rating to be at least 2.5 times the peak inverse voltage seen by each diode under normal operation. This voltage factor of 2.5 allows for voltage transients, unbalance between diodes, adequate derating for long life, and permits safe operation with some shorted diodes.

b. The current rating of the diodes was determined by requiring a minimum overload capacity of 400 percent for one second. This overload rating was determined to be adequate from a preliminary study of generator system capabilities.

c. Diode manufacturers have indicated that diode losses are essentially unaffected by operating frequencies below 5000 cycles per second. This is particularly true of diffused junction diodes which are available in the current ratings chosen for this study. Therefore, rectifier losses were assumed to be constant over the frequency range of 400 to 2000 cycles per second. Diode losses were calculated on the basis of using alloy junction diodes with a junction temperature of 142C (277F) which is a 25 percent derating from the specified maximum of 190C.

4. The silicon diodes used in this study are currently available in 600 PIV ratings. It was assumed, however, that normal improvements in the state of the art will make these diodes available with 800 PIV ratings within a five year period.

TABLE 8.

250 and 500 Kilowatt - Single Bank, Silicon Diode System

	Output Power	250 Kilowatt			500 Kilowatt		
	A. C. System Frequency (cps)	400	1000	2000	400	1000	2000
Diode	D. C. Bus Volts	5 KV	5 KV	5 KV	5 KV	5 KV	5 KV
	Load D. C. Amps	50	50	50	100	100	100
	Amps/3 Phase Bridge	50	50	50	100	100	100
	Amps/Bridge Leg Peak Amps Average Amps	50 16.7	50 16.7	50 16.7	100 33.3	100 33.3	100 33.3
	Diode PIV	800	800	800	800	800	800
	Diodes/3 Phase Bridge	102	102	102	102	102	102
	Total No. Diodes	102	102	102	102	102	102
	Diode Type	JEDEC 1N1190 Except 800PIV	JEDEC 1N1190 Except 800PIV	JEDEC 1N1190 Except 800PIV	W 300 Except 800PIV	W 300 Except 800PIV	W 300 Except 800PIV
	Watts Loss/Diode	20.1	20.1	20.1	35.5	35.5	35.5
	Total Diode Loss (watts)	2052	2052	2052	3621	3621	3621
	PIV, Multip. Factor	2.59	2.59	2.59	2.59	2.59	2.59
	Total Diode Wt. (#)	5.9	5.9	5.9	19.2	19.2	19.2
	Total Diode Vol. (In.^{3})	63	63	63	241	241	241
Resistor	Shunt Resistance (ohms)	40 K	40 K	40 K	20 K	20 K	20 K
	Watts Loss/Resistor	0.97	0.97	0.97	1.93	1.93	1.93
	Total Qty. Resistors	102	102	102	102	102	102
	Total Res. Watts	99	99	99	197	197	197
	Total Res. Wt. (#)	0.6	0.6	0.6	0.6	0.6	0.6
	Dimensions	7/8"L 5/16"D	7/8"L 5/16"D	7/8"L 5/16"D	7/8"L 5/16"D	7/8"L 5/16"D	7/8"L 5/16"D
Capacitor	Shunt Cap. (ufd.)	.01	.01	.01	.1	.1	.1
	Watts Loss/Cap.	.008	.023	.082	.062	.183	.654
	Total Qty. Cap.	102	102	102	102	102	102
	Total Cap. Watts	.82	2.35	8.36	6.33	18.7	66.6
	Total Cap. Wt. (#)	1.9	1.9	1.9	7.03	7.03	7.03
	Dimensions	1.125"L .4"D	1.125"L .4"D	1.125"L .4"D	1.625"L .670"D	1.625"L .670"D	1.625"L .670"D
Conductors	Total Conductor Wt. (#)	.7	.7	.7	2.0	2.0	2.0
	Total Conductor Losses (watts)	17	17	17	71	71	71
	Total Losses (watts)	2169	2170	2176	3896	3908	3956
	Conversion Efficiency (%)	99.139	99.139	99.137	99.22	99.22	99.21

Weight and losses of the interconnecting conductors between the series diodes and the six rectifier legs of the assembled bridge were determined on the basis of a current density of 4500 amperes per square inch. In other larger current rectifier systems it would probably be desirable to decrease conductor weights at a penalty of slightly greater conductor losses by increasing the conductor current density.

2. Cooling and Packaging Considerations

Parametric data of dry weight, required coolant flow, and average coolant temperature for cold-plate cooling is summarized in Table 9 for both 250- and 500-kw rectifier packages. The cooling system calculations are based on the physical properties of monoisopropyl biphenyl (MIPB, per Monsanto Chemical Co.) as coolant.

Data presented in Table 9 is based on the following assumptions:

a. The average coolant temperatures are 122F and 170F.

b. Conduction is the primary method of cooling.

c. Laminar flow is considered for all conditions.

d. Beryllium oxide is used as the diode insulation. The thermal resistance is assumed to be 0.4C/watt from the diode case to the cold plate.

The rectifier package is formed from sheet aluminum. The coolant ducts are brazed or welded to the main section of the cold plate. The beryllium oxide insulation is attached to the cold plate and the diodes are mounted in the insulation. Beryllium oxide insulation is used to avoid a large insulation temperature drop between the diode case and the cold plate. The heat dissipated by the diodes is to be conducted through the beryllium oxide insulation to the cold plate and removed by the coolant flowing in coolant ducts of rectangular cross section. There are two coolant ducts per rectifier-bridge leg.

The coolant flow rates, as given in Table 9, are the minimum required to maintain the derated diode junction temperatures with the package configuration described above.

TABLE 9.

Rectifier Package Coolant Flow Rates and Weights

Output Power	250 kw		500 kw	
Average Coolant Temp.	50C	77C	50C	77C
Coolant (MIPB) Flow Rate (#/Min.)	3.8	12.0	13.2	34.0
Package Dry Weight (#)	49	49	115	115

B. LIST OF MATERIALS AND COMPONENTS

The following materials and components are used in the rectifier package described:

Diodes - Silicon alloy or diffused junctions, nickel plated copper case, glass hermetic seal, hard solder, connections.

Capacitors - Bendix E-200 Series, reconstituted mica insulation, aluminum foil, glass hermetic seal.

Resistors - Wire wound, encapsulated with a silicone coating, tinned copper leads.

Hardware - Carbon steel QQ-S-633, FS1010, Cadmium Plate QQ-P-416.

Mounting Clips - Cadmium plated steel, MIL-S-17919 No. 4.

Solder - Tin 60%, lead 40%.

Insulation - Beryllium Oxide.

Structure & Tubing - Aluminum QQ-A-318 Cond. 1/2 Hard.

Paint - Gray wrinkle enamel, baked.

Conductors - Copper

VI CIRCUIT-BREAKER PARAMETRIC DATA

A. GENERAL APPROACH TO CIRCUIT BREAKER DESIGN

The following paragraphs describe the design approach taken for each major component of the circuit breaker. The basic unit is a three-pole, single-throw latch type (SPST).

a. Dielectric and Current Interruption

The parametric data reflects non-sealed circuit breaker design for use in vacuum environment. Vacuum environment was chosen for its very high dielectric properties and its superior current interruption capacity. The one serious disadvantage of the vacuum environment is the possibility of cold-welding the contact surfaces. Sealed, gas-filled units would, of course, avoid the vacuum weld problem, but at the expense of materially larger and heavier units.

The dielectric property of a vacuum is so high that contact gaps, insulation gaps, and insulation creepages at the 1000- and 2140-volt levels are determined more from a mechanical than from electrical considerations.

b. Contact Materials

The selection of contact material for the electrical contacts was based on the premise: If two metals exhibit mutual insolubility in both the solid and liquid states, those two metals would be excellent candidates for non-welding characteristics. A review of available binary phase diagrams provided several pairs of materials meeting these requirements.

Ag - Ta	Ag - Ir	Ag - Ro
Ag - V	Ge - W	Cu - Nb
Ag - W	Ag - Re	Cu - Re

Because the materials must also have low combined resistivities and have some mechanical strength, the best pair is Cu - Nb (copper - columbium). Ag - W (silver - Tungsten) is next best because of its superior combined conductivity. Copper - columbium was chosen for these breakers.

c. Vapor Shields

Since the circuit breaker may be required to interrupt fault currents as well as normal loads, there will be minute amounts of contact materials vaporized during interruption. Vapor shields surrounding each pair of contacts are provided to cause condensation of those vapors on the shields to prevent their accumulation on the insulation materials.

d. Actuating and Latching Mechanism

A plate-type armature magnet (sometimes referred to as a flat-faced, lifting magnet) was chosen. This was based on two considerations: (1) to provide a force-stroke characteristic compatible with the short-stroke requirements of the contacts; (2) To eliminate sliding parts normally found in conventional plunger solenoids. A permanent-magnet latch was chosen to hold the breaker closed. This type of latch eliminates the continuous power drain required of electrically-held units, and allows the trip time to be controlled to five or ten milliseconds.

e. Configuration

In order to eliminate sliding or rolling conductor or mechanical surfaces the following power circuit is used. Power is brought into the unit through a copper feed-through insulated with beryllium oxide. (Beryllium oxide is used to provide the necessary insulation and provide a good thermal path to the structure.) Molybdenum flexible straps are mounted on the feed-through extension with the copper movable contact mounted on the opposite end of the straps. (Molybdenum was chosen as a compromise between electrical resistivity and mechanical strength needed for the flexing straps.) A columbium stationary contact is mounted by means of beryllium oxide insulation in line with the copper movable contact. Columbium is used for the other feed-through as a common member with the contact.

B. PARAMETRIC DATA AND ANALYSIS

Table 10 shows the power losses to be very low. The parametric data is tempered toward slightly higher weights and lower losses to afford the possibility of radiation cooling in total or a simplified liquid cooling arrangement. The losses also tend to be lowered by the use of copper-columbium combination for the contact materials. The reduction in losses at the 800F condition is caused by a reduction in copper yield strength offsetting its increase in resistivity.

The increased weight of the mechanism at 800F is caused by a reduction in magnetic flux density in the magnetic circuit and to increased resistivity of the electric circuit.

TABLE 10.

LINE CIRCUIT BREAKER PARAMETRIC DATA

Average Coolant Temp.	500F				800F			
Output Power	250KW		500KW		250KW		500KW	
L-N Voltages	1000V	2140V	1000V	2140V	1000V	2140V	1000V	2140V
Contact Losses (watts)	13	3	27	9	12	2.7	24	8
Conduction Losses (watts)	6.7	5.3	10.1	6.4	12.2	9.6	18.2	11.6
Total Losses (watts)	19.7	8.3	37.1	15.4	24.2	12.3	42.2	19.6
Coolant Flow (#/min)	1.25	0.53	2.4	1.0	3.6	1.9	6.4	3.0
Mechanism Wt. (lbs)	1.4	.75	3.3	1.2	3.4	1.8	8.0	2.9
Struct. Wt. (lbs)	1.4	1.35	3.0	1.4	1.5	1.4	3.1	1.4
Total Wt. (lbs)	2.8	2.10	6.3	2.6	4.9	3.2	11.1	4.3

C. COOLING AND PACKAGING CONSIDERATIONS

The entire mechanism of the contactor is mounted directly to a structural base with a wire screen or perforated cover used to protect it from mechanical damage.

The low losses in the unit are expected to be easily dissipated by direct radiation to the external structure or to a cold plate.

Allowance, however, has been made in the weight estimates for use of a cooling tube on the base plate should other heat sink environment be unavailable.

OS-124* is the coolant for 500F designs, and eutectic NaK is used for 800F designs. These were found to be best for this application in the previous one-to-ten-megawatt study.

Coolant flows, listed in Table 10, show the relative flow requirements for a fluid temperature rise of 1C. Higher temperature rise is permissible with proportional reduction in required coolant flow.

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* Registered trademark -- Monsanto Chemical Company

D. LIST OF MATERIALS

The following materials would be used in the circuit breakers described above:

Contacts	Copper and Columbium
Contact Supports	Copper
Contact Arm	Molybdenum
Insulation	Beryllium Oxide
Case and Cover	Type 321 Stainless
Hardware	Type 321 Stainless and possibly a high strength austenitic alloy (such as Discaloy or A-286)
Solenoid	Armco Iron, Copper, Alnico 5
Spring	Inconel X or Rene' 41
Cooling Tube	Type 316 ELC Stainless

A. SELECTION OF SYSTEM PARAMETERS

From the parametric data, NASA specified the following system parameters:

a.	Generator Rotor Speed	20,000 rpm
b.	Generator l-n Voltage	1000 volts
c.	Generator Frequency	1000 cps
d.	Generator Average Coolant Temp.	500F
e.	System Rating	250 kw, rectified 50 kw, a-c
f.	d-c Bus Voltage	5000 volts

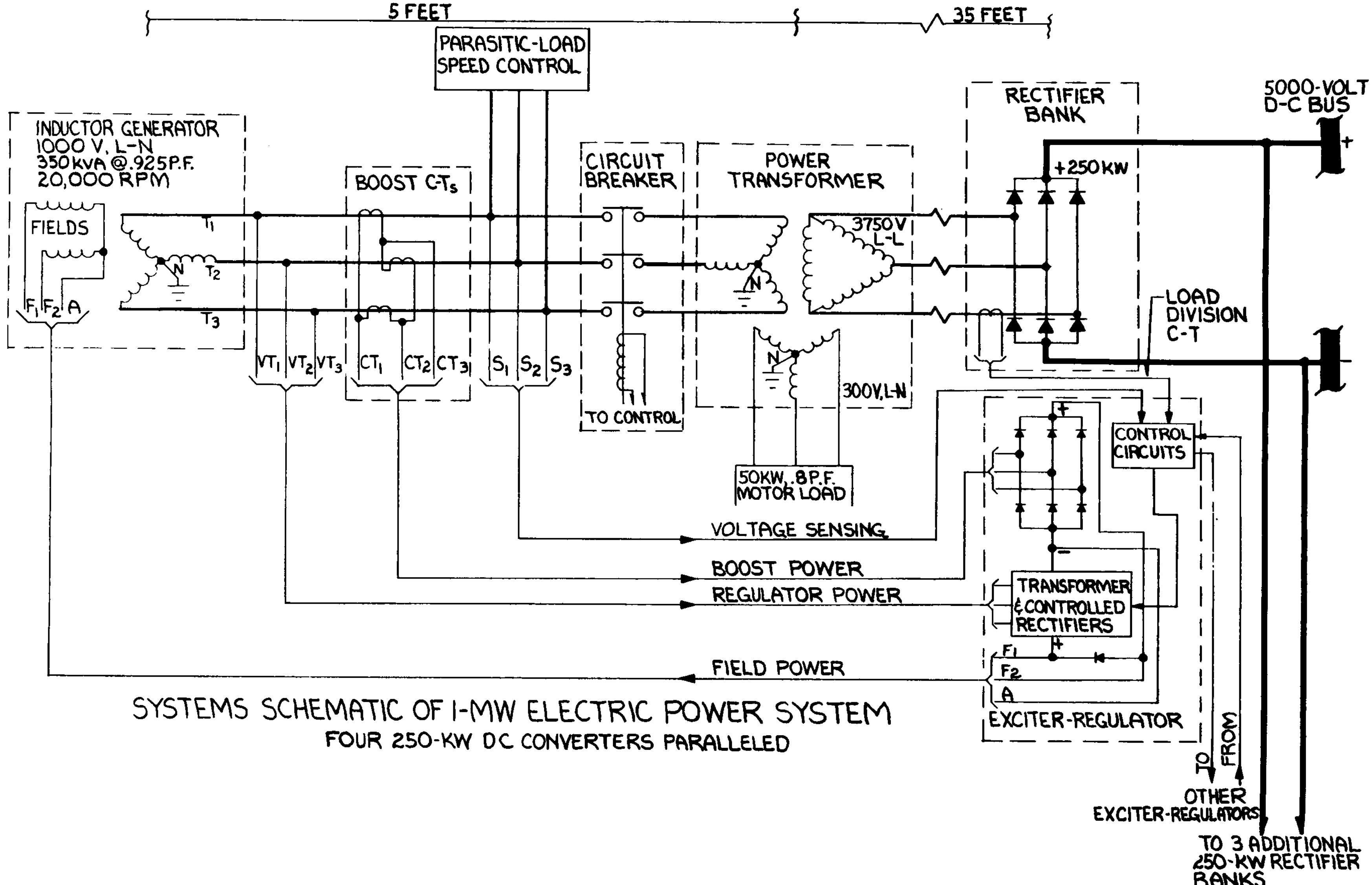
The above parameters do not result in the lightest weight system as an analysis of the parametric data and original specifications show. The above choice was determined on the basis of several additional considerations. These were low voltage a-c motor loads, parasitic-load speed control, overload and short circuit capacity, and paralleling provisions.

The overload, short circuit, and paralleling requirements caused the concept of the exciter regulator to change, and resulted in a small increase in system weight. The exciter-regulator concept chosen is a compromise between increasing generator size and weight and increasing the exciter-regulator weight, rating and complexity. The system chosen will adequately supply these overloads and fault conditions and provide for load division for systems paralleled on the d-c side of the rectifiers. The operation of the exciter is explained in section IX-A. The complete electrical system is shown in Figure 45.

The a-c motor loads considered are induction motors. From a parametric study on various induction motors, NASA determined that 300 volt and 1000 cps produced the best motor performance, weight and efficiency. This low voltage made a two-secondary transformer necessary: See Figure 45.

All of these additional loads caused the required rating of the generator to increase to 350 kilovolt-amperes at 0.925 power factor lag.

SYSTEM SCHEMATIC OF ELECTRICAL POWER SYSTEM



SYSTEMS SCHEMATIC OF 1-MW ELECTRIC POWER SYSTEM
FOUR 250-KW DC CONVERTERS PARALLELED

FIGURE 45.

B. SUMMARY OF PRELIMINARY 300-KW SYSTEM DESIGN

Table 11 summarizes the salient features of the system and its components. Note that the specific weight of this system is higher than those in the original one-to-ten study, by about 0.65 pounds per kilowatt. The generator is the primary source of the increased weight. This increase is caused by three factors: (1) The full rating of the generator is not used as useful output. (2) In general, the ratio of generator total weight to generator electrical weight increases as the rating decreases. In this particular instance the ratio is about 1.4 as opposed to 1.15 in the one-megawatt designs. (3) The one-megawatt generators were operated at 2000 cps while this generator was operated at 1000 cps. At the same speed, the electrical weight of the 1000-cps generator would be 15 percent higher than a 2000-cps generator of the same rating (See Tables 2 and 3 of section II-D. Taking these factors into consideration, the system specific weight would be about 1.8 rather than 2.11.

TABLE 11.

SUMMARY OF SALIENT SYSTEM FEATURES

GENERATOR	
Rating (kw at .93 P. F.)	325
Frequency (cps)	1000
Coolant Temperature (average)	500F
Rotor Speed (rpm)	20,000
Voltage, L-N, Wye (volts)	1000
Efficiency (%)	94.0
Weight (lbs.)	430
Size, L x Dia. (inches)	15x18.5
VOLTAGE & CURRENT TRANSFORMERS	
Coolant Temperature (average)	500F
Connections	See Figure 45
Efficiency (%)	98.3
Weight	145
Size (L x W x H)	23x11x11.5
RECTIFIERS	
Rating (kw)	250
Coolant Temperature (average)	170F
Output Voltage (volts)	5000
Efficiency (%)	99.3
Weight (lbs.)	35.8
Size, L x W x H (inches)	26.5x15.5x6
EXCITER-REGULATOR	
Rating (kw)	3.1
Coolant Temperature (average)	170F
Efficiency (%)	93.8
Weight (lbs.)	15
Size, L x W x H (inches)	12x9x6
CIRCUIT BREAKER	
Coolant Temperature (average)	500F
Efficiency (%)	99.99
Weight (lbs.)	6.8
Size, L x W x H (inches)	14.5x6.25x5.5
SYSTEM	
Input, Shaft Speed (rpm)	20,000
Output Power (a-c kw)	50
Output Power (d-c kw)	250
Direct Voltage	5000
Alternating Voltage	300
Total Losses (kw)	29.5
Efficiency (%)	91.2
Weight; No Weight Penalty* (lbs.)	633
Specific Weight** (lbs./kw)	2.11
Specific Weight, with Weight Penalty	3.43

* Based on 12.5 lbs./kw-loss for generator and transformer
** Based on useful output power

C. GENERATOR WAVEFORM DISTORTION CAUSED BY RECTIFIER LOAD

Since motor-loads were considered as part of the preliminary system, some interest was shown regarding the magnitude and type of generator voltage-waveform distortion. This section describes the effect of the non-linear load on generator waveform and provides curves to determine the overall effect on system voltage droop and harmonic content.

When a rectifying device has about the same power rating as the electric-power generator driving it, the voltage waveform of the generator is distorted. The cause of the distortion is the instantaneous shorting of the generator phases as the current in one rectifying device is transferred to the next rectifying device. This shorting condition is usually referred to as current commutation or simply commutation. Factors which affect the duration of commutation are the impedance in series with the rectifying devices, the magnitude of the current to be commutated, the driving voltage, the number of commutations per cycle of generator voltage, and the type of load on the rectifier. These parameters effect the duration of commutation in the following manner

$$\mu = \text{ARCCOS} \left[1 - (XI/ (E_M \text{ Sin } (\pi/p)) \right] \quad *$$

where:

μ = angle of commutation

I = current to be commutated

E_M = maximum value of L-L voltage

p = number of commutations per cycle of generator voltage

X = impedance in series with rectifier

Figure 46 shows the effect of commutation on harmonic content and line-voltage drop.

In order to make an analysis, the following simplifying assumptions were made:

1. The total current taken from the rectifier is constant.

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*Reference: "Grid Controlled Rectifiers and Inverters", C. C. Herskind, AIEE Transactions, Vol. 53, 1934, pp 926-935.

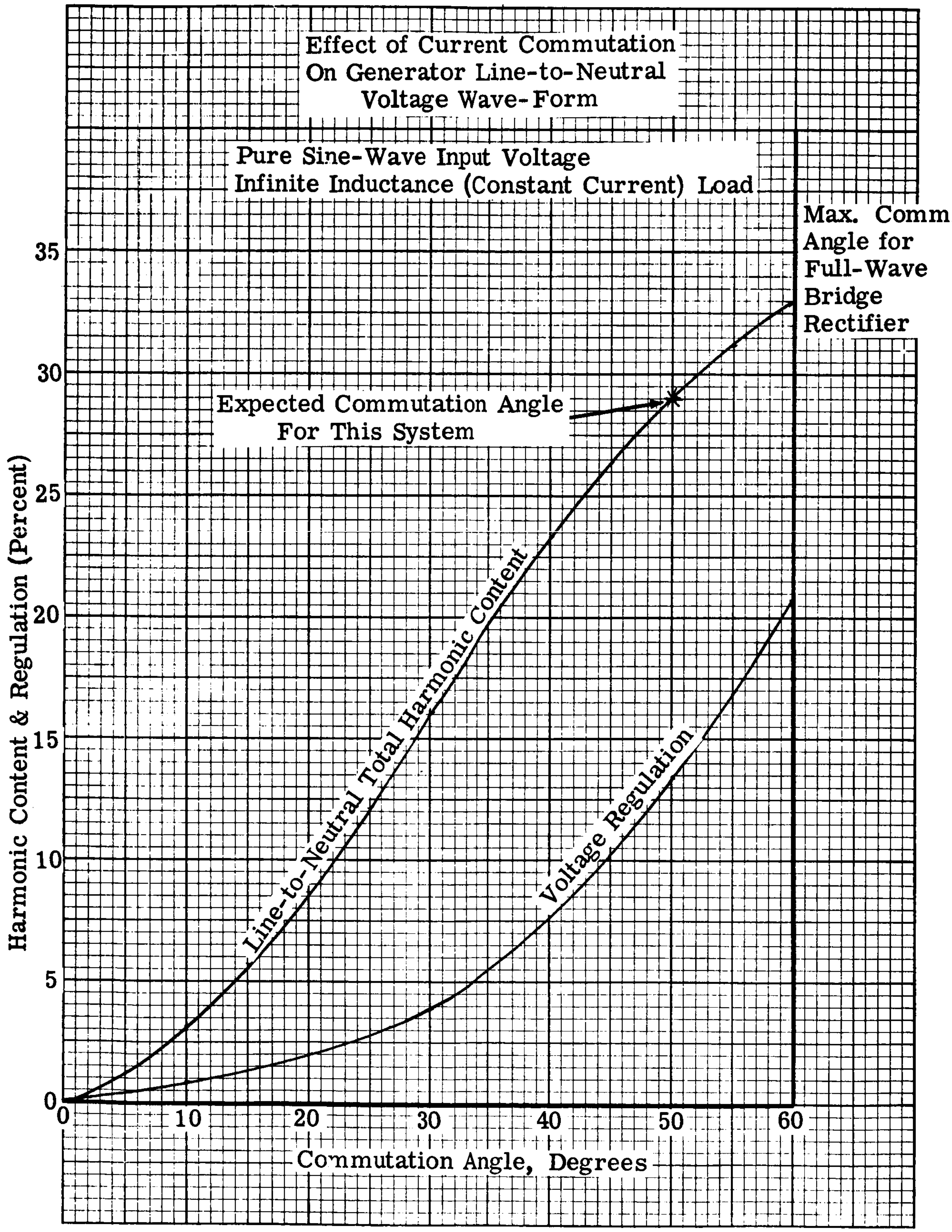

Effect of Current Commutation
On Generator Line-to-Neutral
Voltage Wave-Form
Pure Sine-Wave Input Voltage
Infinite Inductance (Constant Current) Load
Max. Comm.
Angle for
Full-Wave
Bridge
Rectifier
Expected Commutation Angle
For This System
Line-to-Neutral Total Harmonic Content
Voltage Regulation
Harmonic Content & Regulation (Percent)
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
Commutation Angle, Degrees

Figure 46.

2. Because there are six commutations per cycle, in the type of rectifier applied, the sub-transient reactance of the generator is the only generator impedance that will affect commutation.

3. All other impedances, except the transformer leakage reactance, are assumed negligible.

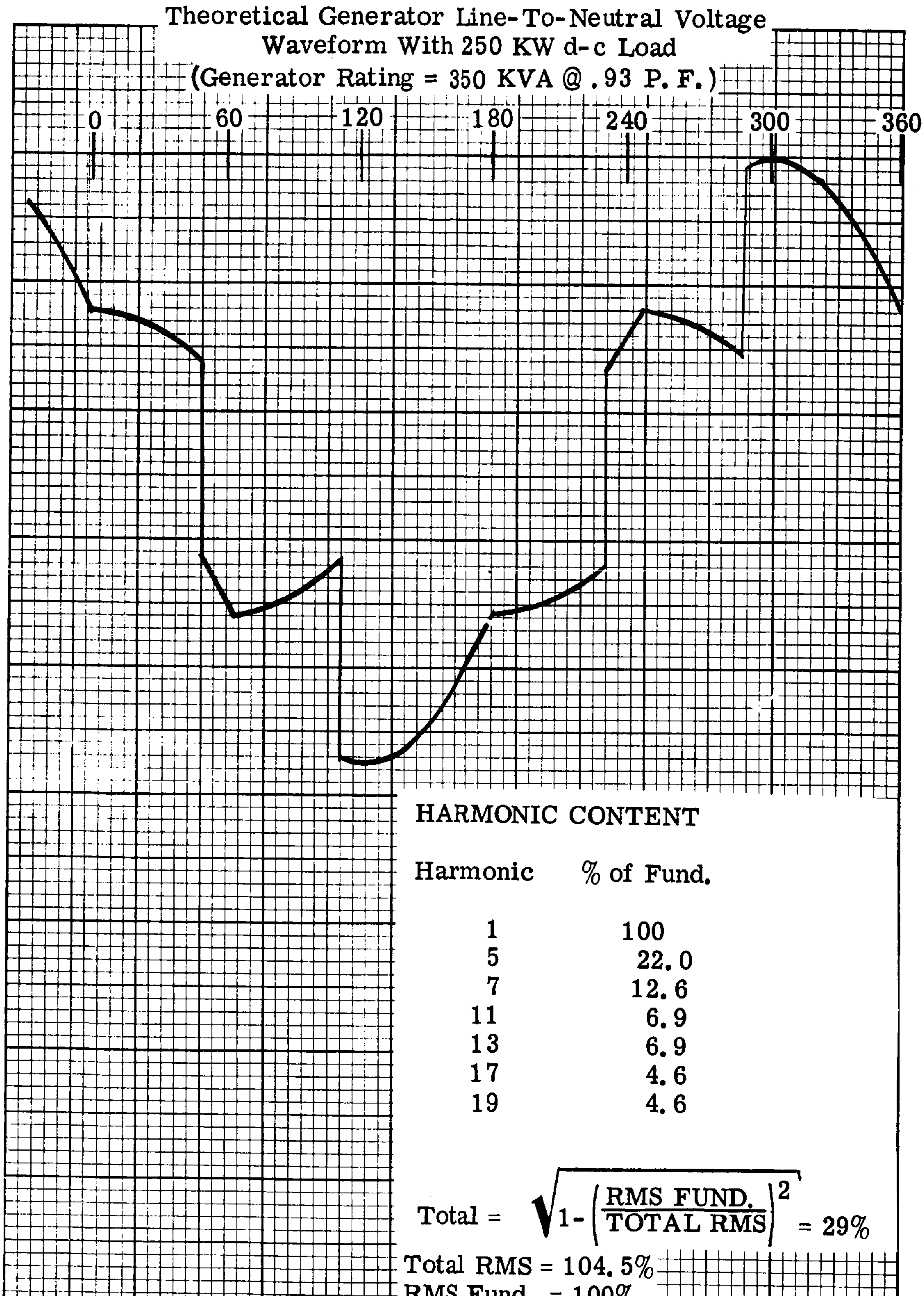
4. The input to the rectifier is a balanced, 1000-cycle-per-second sinewave.

5. The effect of load voltage regulation is neglected.

The effect of neglecting other circuit impedances is small because the transmission line impedance is less than 0.05 ohm, and the resistance of both generator and transformer is quite small. The impedance to commutation, referred to secondary of transformer, is 16.3-ohms generator subtransient reactance and 2.3 ohms transformer leakage reactance. The commutation voltage is 5300 volts peak and the number of commutations per cycle is six. From these values the commutation angle is 49.5 degrees. Figure 47 shows the theoretical waveform and lists the magnitude of the expected harmonics.

Assumptions 1 and 5 make the predicted harmonics higher. If the current is allowed to vary during commutation, the commutation time is less. If the voltage is raised at the input terminals of the rectifier, to compensate for the loss in voltage caused by commutation, the driving voltage will be higher; thereby reducing the commutation time.

The harmonics in the input voltage will tend to be reduced by linear loading on the system. The exact amount is dependent upon the ratio of linear to nonlinear loading and the type of linear loading.



HARMONIC CONTENT

Harmonic	% of Fund.
1	100
5	22.0
7	12.6
11	6.9
13	6.9
17	4.6
19	4.6

$$\text{Total} = \sqrt{1-\left(\frac{\text{RMS FUND.}}{\text{TOTAL RMS}}\right)^2} = 29\%$$

Total RMS = 104.5%
RMS Fund. = 100%

Figure 47.

D. TRANSMISSION LINE

The transmission line is 35 feet long and has 3 conductors. The size, weight and impedance is based on a single wire operating at 150C, and radiating all its losses to zero degrees Kelvin. The impedance of the line is $0.015 + j\,0.043$ ohms per phase. The transmission line weighs 14 pounds.

E. RADIATION

The generator materials should withstand the radiation environment. According to Figure 1 of "The Effect of Nuclear Radiation on Semiconductor Devices"* silicon diodes, with base regions less than one mil wide, may withstand 10^{13} nvt.

No comprehensive data is, however, available for the specific diodes used in these units. No specific data is available for the silicon-controlled-rectifier (SCR) devices. However, the SCR is similar in construction to silicon transistors and the available data on these devices show that a 10^{13} nvt environment would cause considerable damage.

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*REIC Report No. 10, April 30, 1960, Battelle Memorial Institute, Columbus, Ohio.

A. GENERATOR DESIGN FOR PRELIMINARY SYSTEM

1. Electrical

Design 25, Table 2 in section II, was selected as the most desirable 300-kw rating for this application.

Further analysis of the system load indicated that the generator rating should be increased to 325 kw, equivalent to 351 kva at .925 p.f. Because the new rating is very close to the old, the parameters of Design 25 serve as a sound base for the 325-kw generator.

The rating of this generator is: 351 kva, .925 p.f., 1000 volts line-to-neutral, 3-phase, 1000 cps, and 20,000 rpm. The average coolant temperature is 500F.

The importance and effect of design constants RLFUF and RSLTR* were discussed in section II of volume 3. Twelve 325-kw designs were calculated varying RLFUF between .04 and .10, and RSLTR between .125 and .175. The effect of these constants on dimensions, weight, and efficiency are tabulated in Table 12. In Table 12, RLFUF was held constant at .04, .05, .075, and .10. For each value of RLFUF, RSLTR was varied from .125 to .175.

There are four groups of three designs each. Group 1 has lowest weight but efficiency is also lowest. Group 2 has an average increase in efficiency of 0.2 percent over group 1 with an average weight increase of 1.5 percent. Group 3 has an average increase in efficiency of .1% over group 2, but at a weight increase of 8.3 percent. Group 4 has an average efficiency increase of 0.2 percent over group 2, but the weight increase is 14.4 percent.

The generator designs were rearranged for the last part of Table 12. Here RSLTR was held constant at .125, .150, and .175. For each value of RSLTR, RLFUF was varied between .04 and .10. There are three groups of four designs, each group showing an increase in efficiency and weight as RLFUF is increased. The weight range is approximately the same in each group of designs, but the average efficiency is higher in the groups having the highest value of RSLTR.

Close examination of Table 12 shows that Design 25A3 having RLFUF of 0.05 and RSLTR of 0.175 is the most favorable design. It has an efficiency of 94 percent and an electrical weight of 276 pounds. The highest efficiency design is 25A12, but it weighs 317 pounds and exceeded the dimension limitations. There are three designs (25A4, 25A7, and 25A10) which have slightly lower weight and also meet the dimension requirements, but all have lower efficiency.

TABLE 12.

325-KW GENERATOR DESIGN

1000 Volts, 1000 cps, 20,000 rpm 500F Average Coolant Temp.
Single Air Gap = 0.125 in.

DESIGN NO.	DESIGN CONSTANT RSLTR	DESIGN CONSTANT RLFUF	% EFFICIENCY	GEN. ELEC WT. (LBS)	FIELD PWR. (KW)	LOSSES (KW) Fe = Iron Fe	Cu = Copper Cu	W = Windage W	SINGLE STK LGTH (IN)	ROTOR O. D. (IN)	MAX GEN O. D. (IN)	TO-GEN. LGTH (IN)	APPROX. AVG. AC & FLD WDG TEMP. RISE (°F)	P. U. X_d	MAX. ALLOWABLE ROTOR STRESS (psi)	CALCULATED UNIFORM ROTOR STRESS (psi)
Effect of RSLTR																
25A4	.125	.040	93.5	274	3.74	10.0	12.6	.035	1.99	11.66	17.2	11.61	280	1.26	63700	47449
25A7	.150	.040	93.7	273	3.63	9.9	11.8	.035	1.99	11.69	17.5	11.19	283	1.24	63700	47752
25A10	.175	.040	93.8	271	3.63	9.9	11.5	.035	1.99	11.68	17.8	10.86	280	1.23	63700	47723
25A1	.125	.050	93.7	278	3.13	10.2	11.6	.024	2.25	10.80	16.6	11.84	266	1.23	63700	37247
25A2	.150	.050	93.9	277	2.91	10.1	11.0	.021	2.29	10.82	17.0	11.48	256	1.23	63700	37588
25A3	.175	.050	94.0	276	2.94	10.1	10.7	.024	2.28	10.81	17.3	11.18	253	1.22	63700	37561
25A5	.125	.075	93.9	301	2.15	11.0	10.0	.015	2.76	9.78	16.2	12.33	227	1.18	63700	27224
25A8	.150	.075	94.0	300	2.14	11.0	9.7	.015	2.75	9.77	16.6	11.99	222	1.17	63700	27201
25A11	.175	.075	94.1	300	2.15	10.9	9.5	.015	2.75	9.76	17.0	11.72	218	1.16	63700	27168
25A6	.125	.010	94.1	318	1.90	11.3	9.2	.011	2.96	9.16	16.1	12.52	212	1.25	63700	23084
25A9	.150	.010	94.1	317	1.91	11.2	9.0	.011	2.96	9.15	16.5	12.17	208	1.24	63700	23043
25A12	.175	.010	94.2	317	1.92	11.2	8.8	.011	2.96	9.14	16.9	11.91	205	1.23	63700	23012
Effect of RLFUF																
25A4	.125	.040	93.5	274	3.74	10.0	12.6	.035	1.99	11.66	17.2	11.61	280	1.26	63700	47449
25A1	.125	.050	93.7	278	3.13	10.2	11.6	.024	2.25	10.80	16.6	11.84	266	1.23	63700	37247
25A5	.125	.075	93.9	301	2.15	11.0	10.0	.015	2.76	9.78	16.2	12.33	227	1.18	63700	27224
25A6	.125	.100	94.1	318	1.90	11.3	9.2	.011	2.96	9.16	16.1	12.52	212	1.25	63700	23084
25A7	.150	.040	93.7	273	3.63	9.9	11.8	.035	1.99	11.69	17.5	11.19	283	1.24	63700	47752
25A2	.150	.050	93.9	277	2.91	10.1	11.0	.025	2.29	10.82	17.0	11.48	256	1.23	63700	37558
25A8	.150	.075	94.0	300	2.14	11.0	9.7	.015	2.75	9.77	16.6	11.99	222	1.17	63700	27201
25A9	.150	.100	94.1	317	1.91	11.2	9.0	.011	2.96	9.15	16.5	12.17	208	1.24	63700	23043
25A10	.175	.040	93.8	271	3.63	9.9	11.5	.035	1.99	11.68	17.8	10.86	280	1.23	63700	47723
25A3	.175	.050	94.0	276	2.94	10.1	10.7	.024	2.28	10.81	17.3	11.18	253	1.22	63700	37561
25A11	.175	.075	94.1	300	2.15	10.9	9.5	.015	2.75	9.76	17.0	11.72	218	1.16	63700	27168
25A12	.175	.100	94.2	317	1.92	11.2	8.8	.011	2.96	9.14	16.9	11.91	205	1.23	63700	23012

Final design parameters for generator design 25A3 are listed in Table 13.

2. Mechanical

The layout drawing, Figure 48, defines the basic construction of the 325-kw generator. The envelope dimensions and the dimensions of all mating surfaces are given. The alternating current is supplied through terminals T1, T2, T3 and T0. Excitation current is supplied through terminals F1 and F2.

The stator is hermetically sealed to permit operation with a vacuum in the cavity. This sealing will exclude any surrounding fluid and prevent damage to stator components by the potassium vapor existing in the rotor cavity. The seal between the stator and the rotor is a high purity alumina cylinder supported by columbium end pieces. The external frame seal is a thin columbium shell which encloses the columbium end bell to Hiperco 27 frame mechanical joints and the field coil cover joints. The development of a ceramic-cylinder seal was initiated at Westinghouse in 1960, and has performed satisfactorily to date. This sealing concept has been successfully applied to an air-cooled generator. A continuing development program is being pursued to improve the resistance of the seal material to the potassium environment.

Since the mating of turbine to generator will require close coordination with the turbine manufacturer, this aspect was not considered in the preliminary design. It is felt, however, that the large temperature differential between turbine and generator and the relatively massive support will lead to a potentially serious heat transfer problem. It is estimated that the heat transfer by conduction may amount to several kilowatts. An additional heat load will be radiated to the end bell on the turbine end and to the rotor cavity. Since all such heat must be carried to the radiator by the generator cooling fluid which is at a lower temperature than the turbine exhaust fluid, an increase in radiator requirements would be expected. In addition, this may lead to serious temperature differentials in the generator frame and support mechanism. Thermal radiation shielding in the drive end-bell design, as well as rotor windage baffles, is indicated.

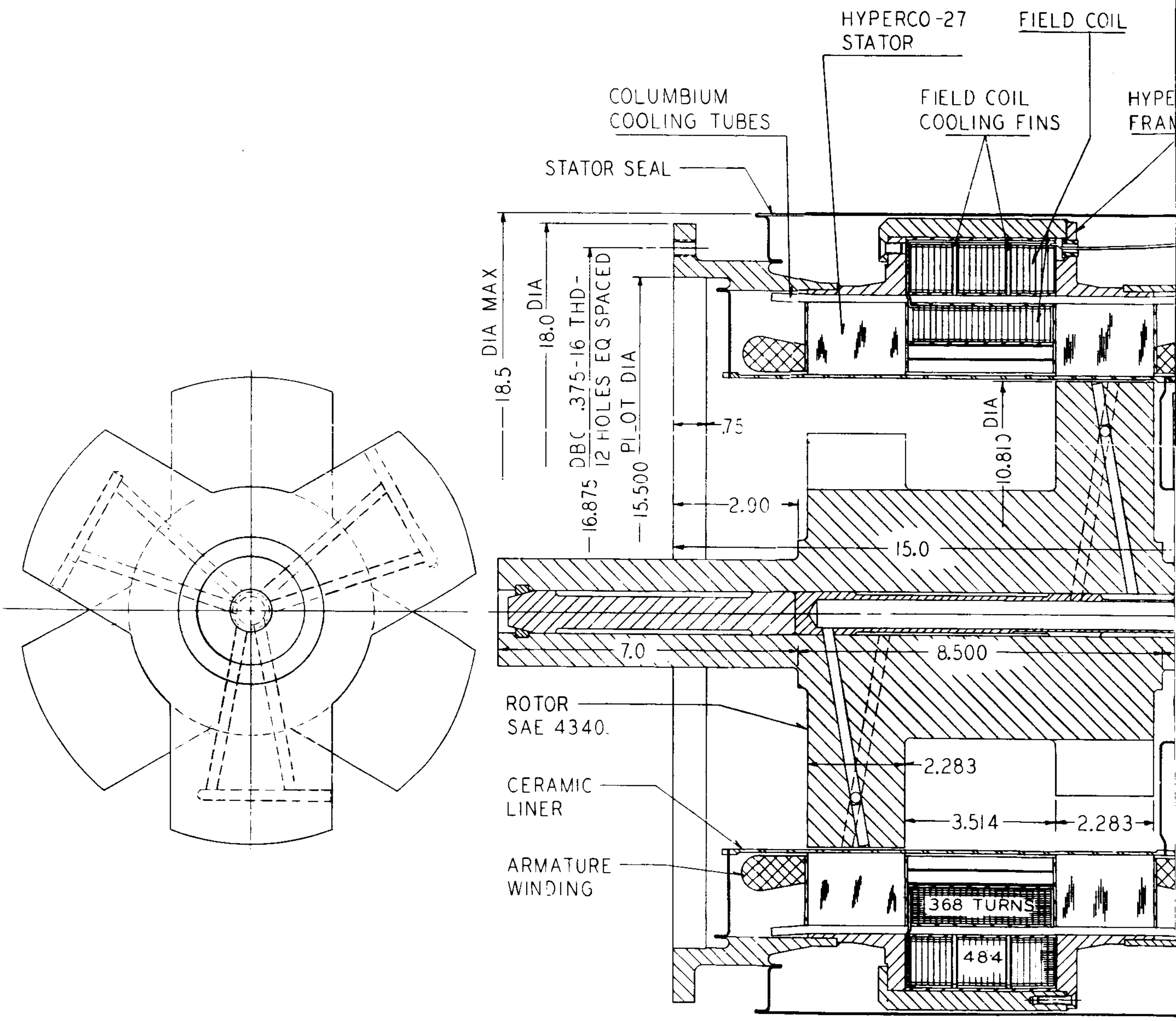
The generator rotor is constructed from a single forging of SAE-4340 steel. All poles are integral with the core to assure mechanical integrity. The pole faces are slotted to reduce eddy-current losses. The filleted sections at the out-board ends of the rotor are provided to relieve bending stresses in the shaft extensions and the tangential stresses at the rotor ends. With the seven-inch shaft extensions illustrated in Figure 48 and assuming the bearing are located two inches from either end, the first critical speed of the rotor is approximately 30,000 rpm.

TABLE 13.

Final 325-kw, Inductor-Generator Design For Preliminary System
(Reference Design 25A3, Table 12)

GENERATOR DESIGN CONSTANTS	
Configuration	Figure 48
Inlet Coolant Temperature	450F
Outlet Coolant Temperature	550F
Stator Coolant Flow	3430 lbs./hr.
Rotor Coolant Flow	561 lbs./hr.
Speed	20,000 rpm
Frequency	1000 cps
Voltage (L-N)	1000 volts
Efficiency	94%
Field Power at Full Load	2.94 kw
Maximum Generator O. D.	18.5 inches
Rotor O. D.	10.8 inches
Total Generator Length Between Flanges	15.0 inches
Average A-C and Field Winding Temperature Rise (Approx.)	253F
X_d	1.22 p. u.
Maximum Rotor Stress	70,000 psi
Calculated Uniform Stress At 20,000 rpm	37,561 psi
Estimated Maximum Harmonics Linear Load (% of Fundamental)	
Single Harmonic	3%
Total Harmonic	5%

GENERATOR WEIGHT BREAKDOWN, lbs.		
Rotor		105.0
Stator Seal	5.22	
Frame Seal	8.00	
Frame	66.40	
End Bell (drive)	36.00	
End Bell (anti-drive)	23.10	
Stacks, Slot Liners, Wedges	73.40	
Coolent Tubes and Plenums	10.93	
Armature Wire (insulated)	19.70	
Field Wire (insulated)	69.20	
Field Coil Insulation and Fins	8.71	
A-C Output Connections and Terminals	4.01	
Stator Total	324.67	324.67
Generator Total (dry)		429.67
Weight of Potassium to Fill Coolant Passages and Plenums		5.06
Total Generator Weight (Wet)		434.73



GENERATOR LAYOUT DRAW

FIGURE 48.

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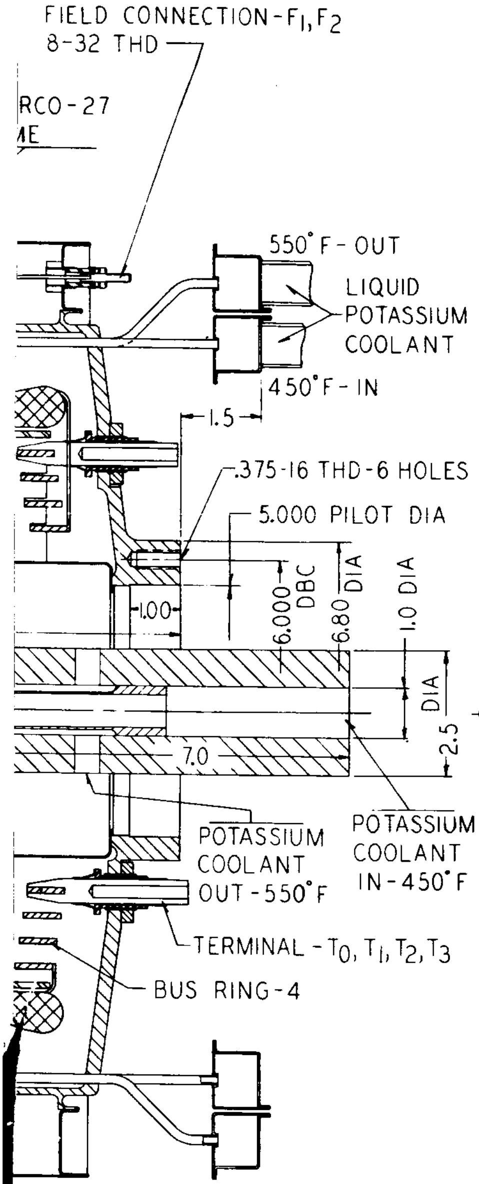

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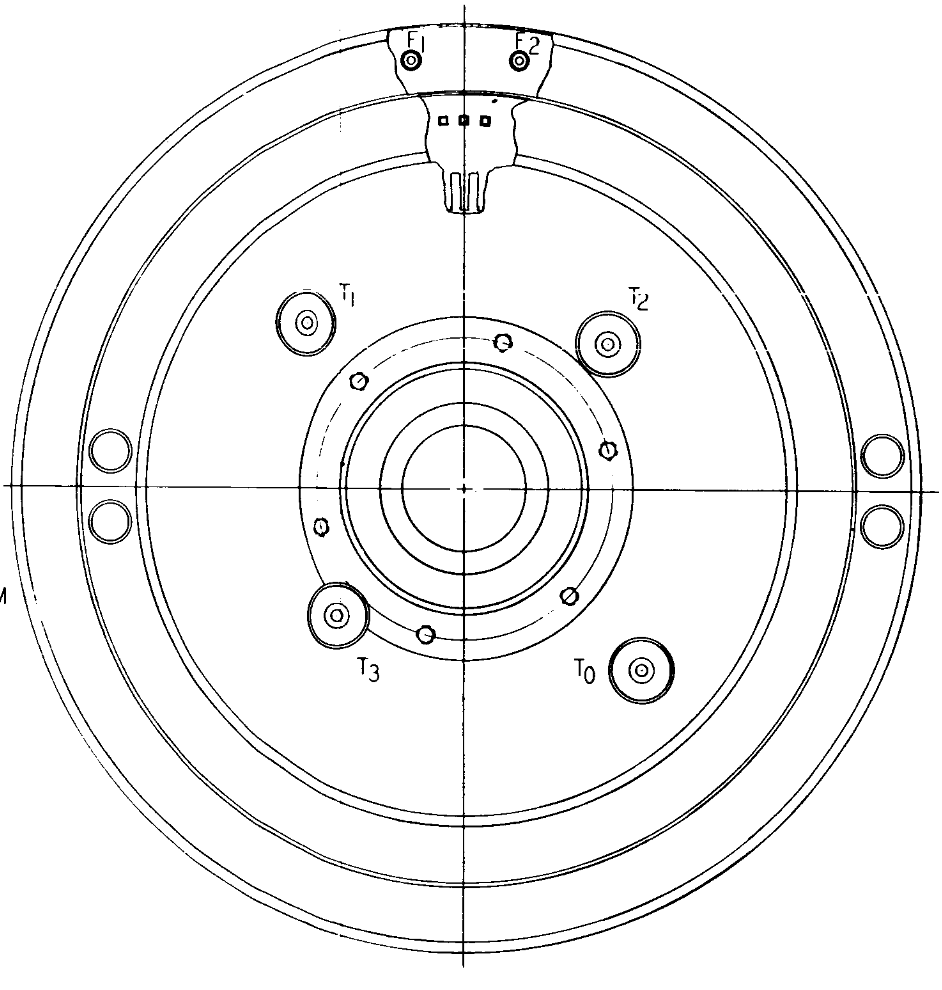


325KW Generator

2

Because the rotor of this generator is large and rotates at a high speed, much analytical effort has been expended to accurately predict the rotor stress and to refine the rotor configuration to reduce the magnitude of stress. In the past, when the rotor-stress levels were well within the material limitations, the rotor stress was calculated by considering an uniform stress averaged over the rotor outer diameter. Now, however, the high-speed, high-temperature rotors operate at, or near, the material maximum stress limit; hence a more refined method of predicting these stresses is needed.

Using a disc with a central hole loaded with diametrically opposed distributed loads as a mathematical model of the rotor, the radial, tangential, and shear stresses are determined at various points in the rotor by superposition.

This analytical method has shown that the average stress of most of the present designs is near the allowable stress level of the material when time, temperature, and creep are included in the 0.5 elongation limit. The maximum stress is a tangential stress in the rotor coolant passage and generally occurs under the pole area.

The high stress levels can be reduced by a prestraining technique. However, the effect of creep under long-time, high-temperature operation may negate the initial benefit of prestraining. It is, therefore, necessary to determine the creep properties of rotor materials as well as the electro-magnetic characteristics of prestrained materials. Short-time testing in this area is currently under way, but long-term data on these and other materials must be developed before a final design is accomplished.

B. GENERATOR COOLING

1. A-C Stator

Stator losses occur in the a-c conductors, the stack teeth, the DBS (depth below slot) iron and in the field coil conductors. The losses are 7939, 1035, 6801, and 2989 watts, respectively. Liquid potassium provides the heat sink for these losses, entering the frame at 450F, and leaving at 550F. The coolant flows through U-tubes extending through both stacks and the field coil and discharges at the anti-drive end. Several placement methods and locations for the tubes have been studied, with particular attention to the stator stack region. These include placement of the cooling tubes in: (1) The conductor slots; (2) The slots at the outer diameter of the punchings; (3) The stator frame.

The third method was chosen because the first method increased eddy-current and iron losses, while the second method either increased the heat-flow path or cancelled the effect of laminating the core by shorting out the laminations depending on whether a weld or brazed bond was used. By placing the cooling tubes in the frame, the tubes could be brazed into place without shorting out the laminations. This approach poses an apparent disadvantage as there is no positive bond between the major heat source -- conductors and core -- and its sink. However, three factors tend to overcome this apparent disadvantage:

a. The frame will operate at a lower temperature than the stack, which will result in reduction of the gap between these parts, and any increase in stack temperature would tend to reduce the gap.

b. Good thermal contact of the tube to the frame will tend to reduce the heat flow path in the frame.

c. Final machining of the frame, following brazing, can be utilized to reduce the coolant tube wall thickness in this area.

A tube of square cross-section was chosen to facilitate assembly and to reduce the effective wall thickness of the tube.

The tubes in the frame are placed over each tooth in stator stack. One tube forms a coolant inlet and the adjacent tube is the outlet. The tubes are thus preformed hairpin shapes. Fifty-four connections are required from each coolant plenum. Further analysis may show that a greater pitching is allowed, resulting in a reduction in total coolant tubes. Testing of an operating liquid metal cooled generator, currently under development, will furnish data for this analysis. Analysis of obstructed flow patterns will also be reviewed. Stator frame construction will be the subject of extensive review and analysis for future development.

The method chosen for cooling the a-c stator leaves two major resistances to heat transfer. These are gaps between (1) the a-c conductor and stack (slots) and (2) the stack and frame. This resistance is caused by the relatively low equivalent heat-transfer coefficient through a vacuum. The resistance in the conductor slot gap is reduced by points of contact in each slot. The resistance of the stack-to-frame gap is reduced by shrinking the stack into the frame and further reduced by the relative thermal expansions of the two parts.

The effect of contact in the conductor slot is illustrated by Figure 23 of volume 3. Average and maximum conductor temperatures and maximum iron temperature are presented. These values were calculated assuming a uniform distribution of points of contact between the conductor and the teeth over the full stack length. Because the contact is expected to be non-uniform in the actual generator, the maximum iron temperatures will exceed those indicated. Maximum conductor temperatures may also be higher than shown, depending upon the distance between the contact points and the end turn. The magnitude of these temperature increases must be evaluated experimentally.

Figure 23 of volume 3, while drawn for a vacuum condition, can also be used to show the effect of using a gas in the stator cavity. The use of a gas increases the effective contact. Thus, with no physical contact the results of similar calculations with CO_2 correspond to about 5 percent contact.

The effect of the second gap (between the punchings and the frame) upon stator temperature is illustrated by Figure 24 of volume 3. The temperature drop from the coolant to the punching material versus percent contact is shown. By shrinking the punchings into the frame the contact pressure is increased. This, plus appropriate choice of surface finish (32 to 64 microinches) on the mating parts, will lead to an improved heat transfer coefficient. The degree of contact obtainable is primarily a function of the allowable stress in the frame and stack material (Hiperco 27). An alternate approach is to sandwich a thin foil or plating of a relatively soft material in the gap. While this introduces an "air gap" in the magnetic path, it should permit a lower pressure between the stack and the frame while providing good contact. This approach will require experimental evaluation to determine its effect on the thermal resistance of this gap.

While the conductor slot gap has little effect on the conductor temperatures for contact ratios over 5 percent, the contact between stack and frame is much more significant. The most desirable means for obtaining contact in this region is experimentally.

2. Field Coil

The field coil loss is 2989 watts. This loss must be dissipated to the surrounding frame and cooling tubes. The maximum temperature level existing in the field coil is determined by the total thermal resistance, the heat-sink temperature, and the heat generated in the field coil.

Should a single field-coil box be used in the generator, the maximum temperature at the center of the coil would be over 1500F. This temperature estimate was based upon the results of tests on a similar generator in the Westinghouse Aerospace Electrical Division Laboratory. Such a temperature level would be intolerable, since neither wire nor insulation could be obtained for such conditions.

The field coil of this generator has been designed to reduce this temperature level by creating a shorter heat transfer path and larger heat transfer area. The former was accomplished by placing part of the coil between the a-c conductors and the coolant tubes, and the latter by placing fins on the cooling tubes. The estimated maximum temperature for this coil design is 1000F.

3. Rotor

The rotor pole face losses and windage losses are 2250 and 813 watts, respectively. To cool the rotor liquid potassium is introduced at the anti-drive end, passes through the rotor core and each pole and is then discharged at the anti-drive end in a counter flow path. The poles are cooled by diverting the liquid radially from the central passage to the pole tip at each rotor-pole section. The size and location of the rotor coolant passages illustrated on the layout represent the configuration based on current studies of rotor cooling. Further investigation is being conducted in this area based on analytical and test results. The configuration can change extensively when more is known of the allowable temperature limits on the surface of the rotor and the temperature effect on the electro-magnetic design. This one area represents a subject for extensive future investigation.

C. MECHANICAL MISALIGNMENTS AND ELECTRICAL FAULTS

1. Magnetic Forces

a. Radial Displacement

When the rotor of an electromagnetic machine is displaced radially from its normal position, a force is produced which tends to move the rotor in the direction of the displacement. This force has been calculated as a function of rotor displacement and is shown in Figure 49.

b. Tilted Rotor

When the rotor of an electromagnetic machine is cocked or tilted about its center, Point 0 of Figure 50, from the position of perfect alignment, the ends will be displaced at points A and B, and a torque will be produced which tends to produce further misalignment. Torque and displacement have been calculated for design 25A3 for three angles and are tabulated below.

Rotor Tilt (degrees)	Displacement at Points A and B (inches)	Torque About Point 0 (inch-pounds)
1.0	.071	1430
.5	.036	715
.3	.021	429

2. Generator Losses and Fault Capacity

The losses and efficiency of this generator at various load conditions are tabulated in Table 14. Five load and power factor conditions are given. The loads are based on d-c loads of 25, 50, 75, and 100 percent with the a-c load constant for each condition. The 150 percent over-load condition is based on a 0.95 power factor.

Table 14 also shows the fault capacity for three types of faults. The magnitude of alternating current, at each fault condition, is given for three values of generator excitation.

Figure 51 provides saturation curves for generator load conditions of no load, 150-percent load, and 100-percent load at 3 power factors. A curve of three-phase fault current for various values of generator excitation is also included.

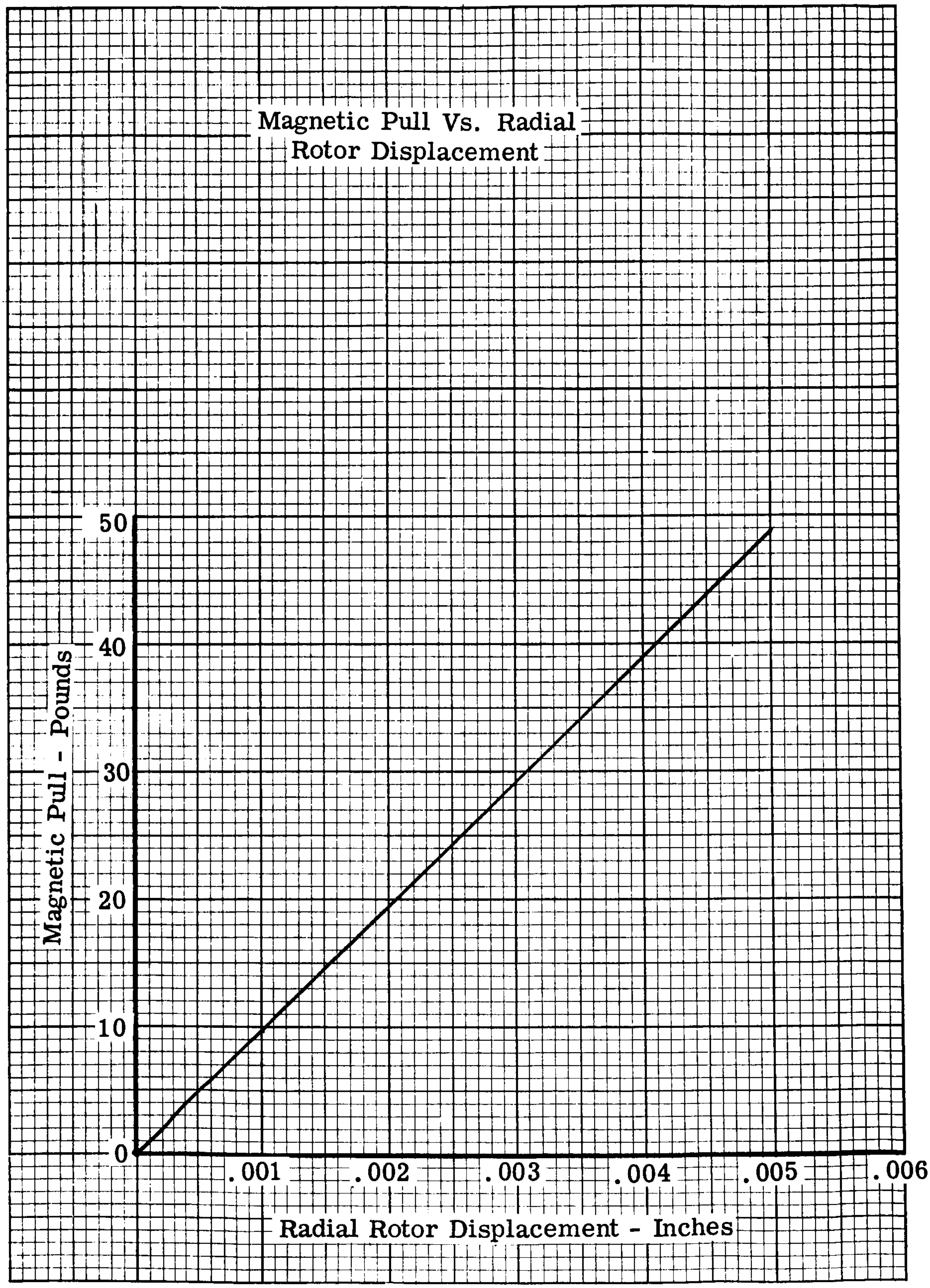
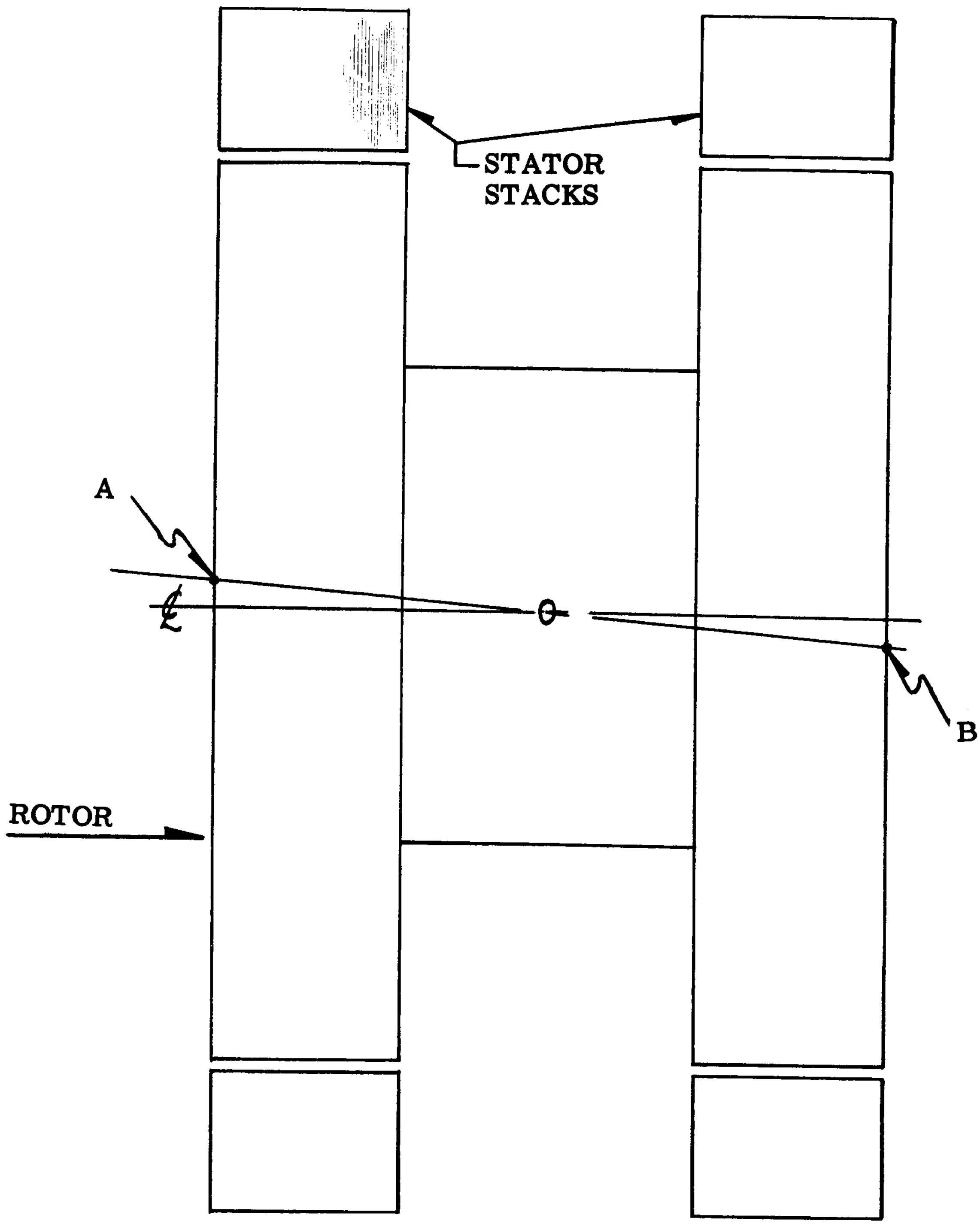

Magnetic Pull Vs. Radial Rotor Displacement
Magnetic Pull - Pounds
50
40
30
20
10
0
.001
.002
.003
.004
.005
.006
Radial Rotor Displacement - Inches

Figure 49.



ROTOR-STATOR SCHEMATIC

FIGURE 50.

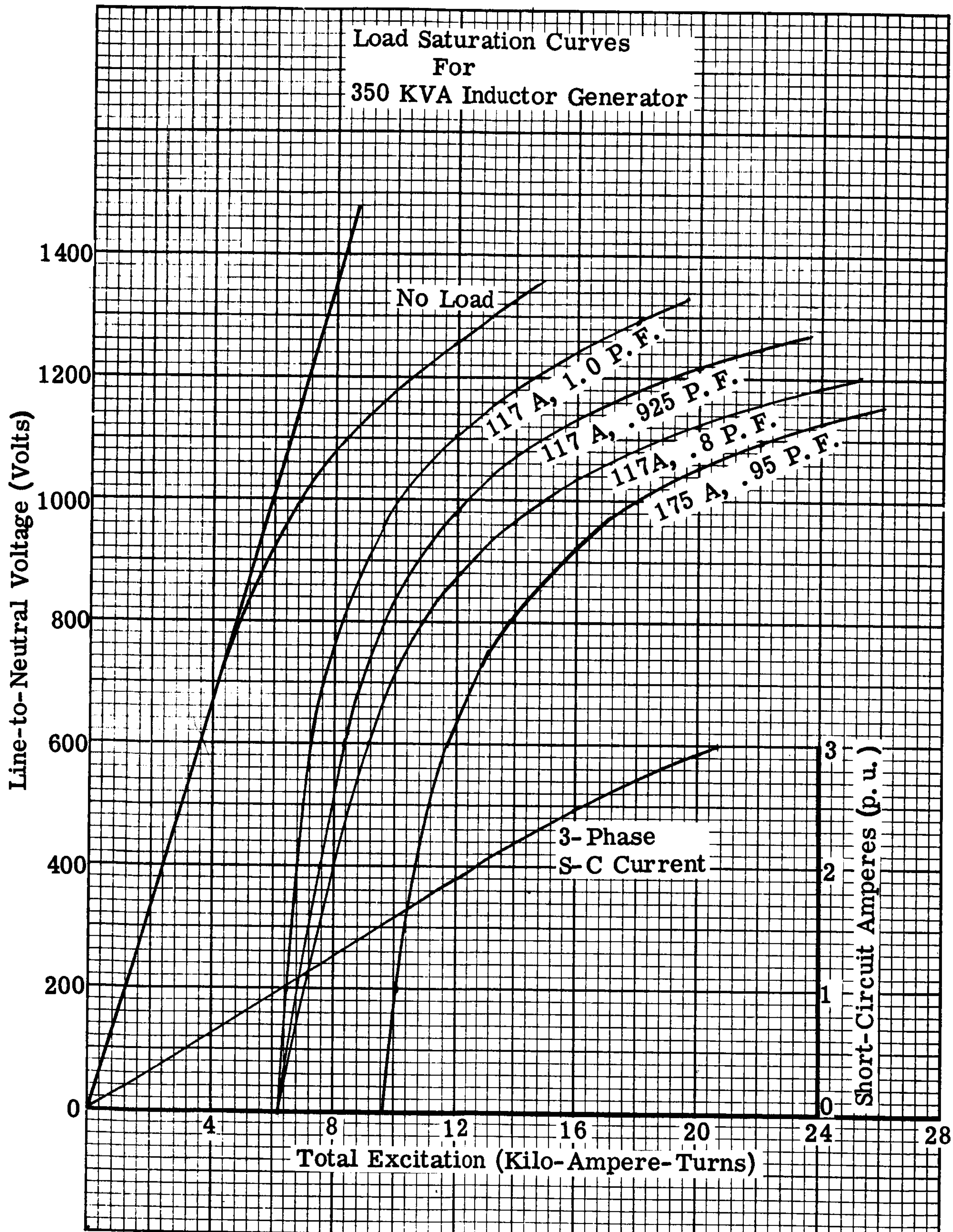
TABLE 14.

Generator Losses and Fault Capacity

Efficiency and Losses At Various Load Conditions					
Line Current, Amperes Power Factor KW Output	57.3 .79 136	78.4 .85 200	100 .88 264	117* .925 325	175 .95 499
Copper Loss, Watts Iron Loss, Watts Total Loss, Watts	3940 10118 14058	6160 10118 16278	9130 10118 19248	10877 10118 20995	25200 10118 35318
Percent Efficiency	90.6	92.5	93.2	94.0	93.4

Fault Capacity For 3 Values of Excitation			
Excitation, Amp-turns	6217	12,514	20,643
Short Circuits, Amperes 3-phase Line to Line Line to Neutral	 117 141 241	 234 282 482	 351 423 743

* Rated Current


Load Saturation Curves
For
350 KVA Inductor Generator
Line-to-Neutral Voltage (Volts)
1400
1200
1000
800
600
400
200
0
No Load
117 A, 1.0 P.F.
117 A, .925 P.F.
117A, .8 P.F.
175 A, .95 P.F.
3-Phase
S-C Current
Short-Circuit Amperes (p.u.)
3
2
1
0
4
8
12
16
20
24
28
Total Excitation (Kilo-Ampere-Turns)
Figure 51.

D. GENERATOR MATERIALS

A detailed discussion of generator materials was presented in section III-A of volume 1. The materials which will be used in the 325-kw generator are listed below:

Summary of Construction Materials

Component(s)	Material
Rotor (1,2)	4340 Steel
Coolant tubes (2)	Columbium alloy, B-33
Seal end supports (1), Frame mounting brackets (1)	Columbium alloy, B-33
Ceramic Seal (1)	Alumina (99.5% pure)
Frame parts, punchings	Hiperco 27 alloy
External frame seal	Columbium alloy, B-33
Current carrying members	Copper, Nickel-plated
Slot liners, terminal insulators	Alumina (99% pure)
Wire insulation	Glass bonded refractory
Field Coil Insulation	Mica Sheet
Punching insulation (inter-laminar)	Aluminum-ortho-phosphate
Stack end insulation	Mica Sheet

1 - Exposed to potassium vapor
2 - Exposed to liquid potassium

A. ELECTRICAL DESIGN

1. Basis of Design

In the parametric data portion of this study program, the excitation system design contained no provisions for parallel operation or for supplying excitation power during overload and fault conditions. However, these requirements were added to the preliminary design; thus necessitating a modification of the original excitation system design.

Specifically, new design objectives of the excitation system include the capability to supply the excitation required for 1.5-per-unit load and 3-per-unit short circuit conditions. The ability to divide loads, at the d-c bus, among four paralleled generating systems was also included.

The modified excitation system consists of an exciter-regulator which supplies power to a controlled field winding (F1) and an auxiliary current transformer which supplies power to an auxiliary field winding (F2), see Figure 45. The effect of the two fields is additive: The current transformer supplies a rectified current proportional to the total generator load current; while the exciter-regulator supplies the remaining current required for rated generator output voltage. Under certain abnormal load conditions, specifically short circuits, the output of the exciter-regulator collapses and the auxiliary current transformer supplies current to both field windings in parallel.

2. Basis of Design

The following table lists the important parameters for the conceptual exciter regulator.

Generator Rating — 350 kva, 0.925 p.f., 1000 cps

Generator Excitation Requirements:	Field Power (kw) Field F1	Field Power (kw) Field F2
1 p.u. load	1.9	1.2
1.5 p.u. load	3.2	2.9
3 p.u. short circuit	1.8	7.5

The preliminary design of the exciter-regulator is based on the following considerations and assumptions:

a. The normal steady-state voltages applied to the rectifiers and controlled-rectifiers in the power amplifier and auxiliary rectifiers are selected so that the applied peak inverse voltage is 50 percent of their maximum ratings. This gives a safety factor to allow for system bus voltage transients.

b. The maximum steady-state operating temperature of the controlled-rectifier junctions is held to a maximum of 93C which is a 25 percent derating from their maximum allowable junction temperature of 120C. This derating increases the reliability of these devices.

c. The magnetic amplifier design and packaging will result in a maximum internal temperature rise of 50C above the cold plate temperature. This will result in very small changes in core characteristics.

d. The design and packaging of the transformers will result in a maximum internal temperature rise of 200C above the cold plate temperature. This will eliminate the need for special high temperature insulation.

e. Methods and required circuits for system voltage buildup are not considered.

f. The load sensing current transformer required for the load division circuit in parallel operation is not included in this design study.

g. The use of silicon semiconductors assumes that sufficient shielding against nuclear radiation will be employed.

2. Description of Circuits

The exciter-regulator can be divided into four basic functional blocks: (1) voltage error detector, (2) load division circuit, (3) preamplifier, and (4) power amplifier. The exciter-regulator design is shown in schematic diagram, Figure 52, which also includes a fifth functional block containing the bridge rectifier required for the auxiliary current transformer.

The voltage error detector circuit consists of a sensing transformer, bridge rectifier, and zener diode voltage reference bridge. The average of the three-phase generator output voltage (applied to terminals T1, T2, T3 and N) is sensed, rectified, and then compared with the reference voltages of two matched zener diodes. Any deviation from the desired generator voltage results in an error signal being applied to a control winding in the preamplifier.

The load division circuit consists of a bridge rectifier and an L-C filter network being fed from input terminals X1 and X2. The output of this network is in series with a portion of the voltage error detector circuit such that, in parallel operation, the output of the voltage error detector is a function of both the system bus voltage and the load division circuit. (A more complete description of this circuit is described below.)

The preamplifier consists of three half-wave magnetic amplifiers (AR1, AR2, and AR3) operating from a three-phase transformer, a bias current supply regulated by a zener diode (CR11), and an RLC network which feeds back the output voltage of the power amplifier to a compensation winding in the preamplifier. The gate winding of each magnetic amplifier is connected to the gate terminal of an appropriate controlled rectifier in the power amplifier. The algebraic sum of the ampere-turns in the control windings (from the detector, bias, and compensation circuits) determines the firing angle of each magnetic amplifier with respect to the positive half cycle of voltage applied to each one.

The power amplifier contains a three-phase power transformer and a full-wave bridge rectifier consisting of three controlled rectifiers and three conventional rectifiers. The power transformer steps down the system voltage (applied at terminals P1, P2 and P3) to a level compatible with the voltage ratings of the rectifiers in the rectifier bridge. The controlled rectifiers are fired by the gate voltages applied from the preamplifier. The firing angle of each controlled rectifier is proportional to that of the corresponding magnetic amplifier in the preamplifier, and this firing angle determines the amount of excitation power supplied to the controlled field winding through output terminals F1 and A.

The auxiliary rectifier consists of a three-phase bridge rectifier and a "spill-over" diode (CR27). Input current from the auxiliary current transformer (through terminals CT1, CT2, and CT3) is rectified and fed to the auxiliary field winding through output terminals F2 and A. Whenever the output voltage to field F2 exceeds that to field F1, output current will overflow into field F1. The rectifiers in this circuit also provide a commutation path for the field current which results from the emf generated in field F1 during that portion of each cycle when the controlled rectifiers are not conducting.

. Description of Operation

During normal isolated system operation the auxiliary current transformer supplies excitation current to field F2 proportional to the load current of the system. This amount of excitation, at a given load impedance, is not sufficient to support rated system voltage. Therefore, in the exciter-regulator, the voltage error detector which senses the generator a-c output voltage adjusts the output of the exciter-regulator (to field F1) to a level which will support and maintain rated system voltage. During fault conditions, especially short circuits, the output voltage of the power amplifier may be less than that of the auxiliary rectifier. In such a case the auxiliary current transformer supplies partial or full current to field F1 as well as full current to field F2.

During parallel system operation the outputs of the load division circuits of each exciter-regulator (terminals E1 and E2, Figure 52) are also paralleled. In each system a current signal is received from a load sensing current transformer placed at the input to the system rectifier bank. This current signal is proportional to the d-c load current of the system and is fed into the load division circuit (terminals X1 and X2). With equal load currents in all systems the voltages developed across terminals E1 and E2 are equal and no effects are produced in any voltage error detector circuit. However, when one system is supplying more (or less) than its share of d-c load current, the developed voltage in its load division circuit (across R16) will increase (or decrease), thus forcing a change (viz. the voltage across R17) in the detector circuits of all paralleled systems. The effect is to decrease the excitation to the system producing more than its share of load current and to increase the excitation to the system producing less than its share of load current.

EXCITER-REGULATOR SCHEMATIC

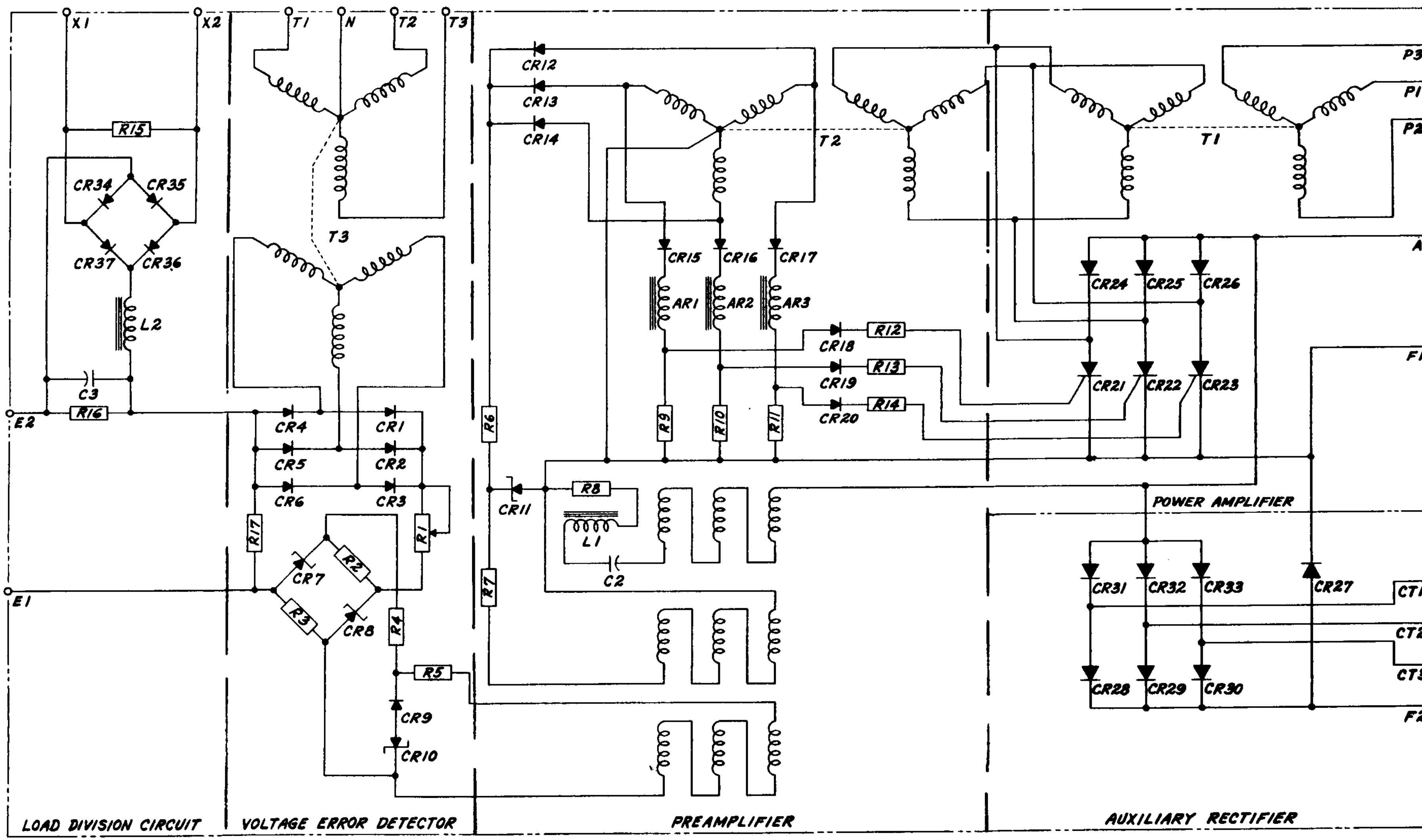


FIGURE 52.

B. MECHANICAL DESIGN

1. General

The exciter-regulator package is formed from aluminum sheet to achieve low weight and high thermal conductivity. Cooling is accomplished by conducting losses from electrical components to a cold plate. The cold plate is formed aluminum sheet with coolant ducts welded to the bottom of the plate. It serves as a structural base for the unit as well as a cooling means. The package is a bolt-down design with four mounting points.

Conduction is the primary means of cooling the electrical components, and laminar-flow liquid convection through coolant tubes is used to maintain the required cold-plate temperature. Monoisopropyl biphenyl (MIPB) is the chosen coolant, with the average temperature assumed to be 170F.

All semiconductor junction temperatures are derated 25% from the maximum junction temperature specified by the manufacturer. Beryllium oxide is used as insulation for all semiconductors to obtain low thermal resistance with good electrical insulating properties.

Transformers within the exciter-regulator are cooled by conduction of the losses through an epoxy resin (filled with pellets of beryllium oxide) to the cold plate. The mixture of epoxy and beryllium oxide exhibits very good thermal conductivity, high strength, high electrical resistance, and a coefficient of expansion equal to that of aluminum.

All other components are mounted directly to the cold plate except for miniature resistors and semiconductors which are mounted on aluminum printed circuit boards. Temperature sensitive components are mounted near the coolant inlet and separated from high temperature or high heat loss components.

The minimum coolant flow rate and pressure drop as specified in Table 15 are those required to maintain semiconductor junction temperatures below the derated maximum at all conditions of exciter-regulator output.

2. Specific Design Information

a. Exciter Regulator

Design details and information for the exciter-regulator package are listed below.

TABLE 15.

Exciter-Regulator Design Information

Maximum Outline Dimensions	Figure 53
Calculated Weight	
With Coolant	15.00 lb.
Without Coolant	14.80 lb.
MIPB Coolant	
Average Temperature	170F
Inlet Temperature	165F
Exit Temperature	174F
Flow Rate	218 lb/hr.
Pressure Drop	0.10 psi (3.1 in. H_2O)
Power Loss	
0.5 per unit system load	185 watts
1.0 per unit system load	211 watts
1.5 per unit system load	318 watts
3.0 per unit three-phase short circuit.	303 watts

b. Auxiliary Current Transformer

The auxiliary current transformer is a three-phase design utilizing a three-phase transformer core and multiple primary turns. The current transformer is packaged with the main system transformer and further design details are included in that section. The design is such as to cause the current transformer to saturate at a three-per-unit, three-phase load current condition. This limits three-phase, short-circuit faults to three-per-unit fault current.

Design information, such as power losses and weights, are not identified specifically for the auxiliary current transformer because such details are included with the main system transformer design.

EXCITER-REGULATOR OUTLINE DRAWING

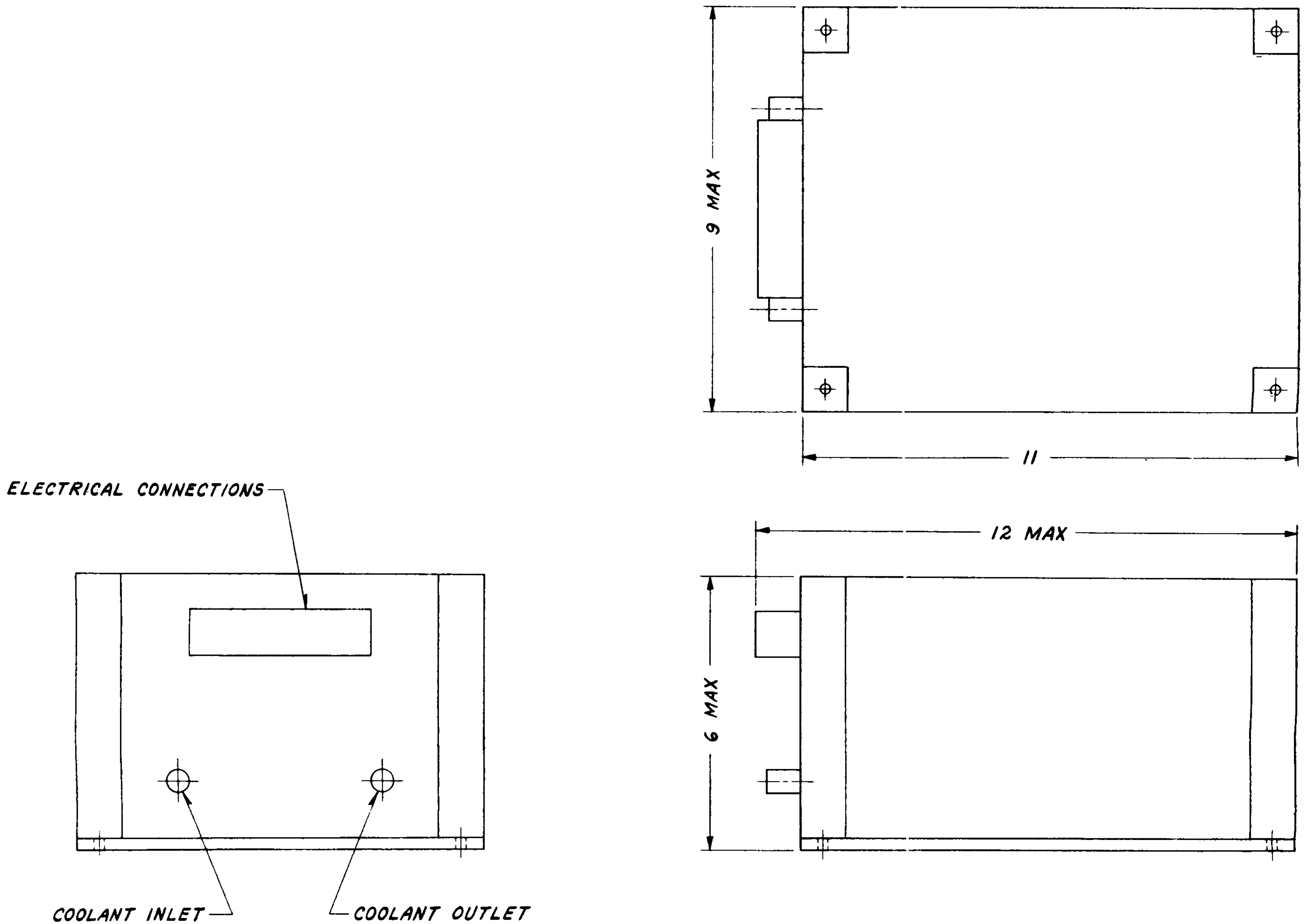


FIGURE 53.

C. MATERIALS AND COMPONENTS

1. Components

The electrical components listed below have been selected for the exciter-regulator. A description of the component and the estimated operating temperature of the hottest component within each group is given.

TABLE 16.

Electrical Components for Exciter-Regulator

Component	Description of Components	Estimated Operating Temp. -C
Controlled-Rectifier	Stud mounted, heremetically sealed, silicon junction.	93 (junction)
Rectifiers	Stud mounted, hermetically sealed, silicon junction.	130 (junction)
Diodes	Glass encapsulated, hermetically sealed, silicon junction.	100
Resistors	Encapsulated wire-wound.	100
Potentiometer	Encapsulated wire-wound.	100
Capacitor	Mica impregnated with thermal setting polyester and hermetically sealed.	120
Saturable	80% nickel-iron alloy toroidal core incased with silicone grease in aluminum core box. Wound with ML insulated magnet wire and insulated with mylar tape.	130
Transformer	Grain oriented silicon steel E cores wound with ML insulated magnet wire and insulated with teflon.	280

2. Materials

The following materials are used in the mechanical design of the exciter-regulator package.

a. Aluminum QQ-A-318 Cond. 1/2H
b. Clips, Component - Nickel plated Steel
c. Solder, Tin Lead 60-40
d. Epoxy 100% Solid
e. Epoxy 53841GD Blue Thixotropic epoxy resin fluidized powder.
f. Silicone Rubber
g. Glass Filled Epoxy Nema G-10
h. Beryllium Oxide
i. Extruded Teflon
j. Steel QQ-S-633-FS1010
k. Carbon Steel QQ-S-633-C1137
l. Clear Phenolic Varnish, Vacuum pressure impregnated
m. Teflon Impregnated Glass Cloth
n. Silicone Micarta Nema G-7
o. 8468-2 Tape, Thermosetting Glass Tape
p. Varnish, Silicone D. C. 997
q. Nickel Plating
r. Gold Plating
s. Hook up wire, teflon insulated copper wire

D. RECOMMENDED AREAS FOR FURTHER STUDY

During the course of this study program, certain problem areas appeared which will require further study in order to obtain a satisfactory system.

1. Susceptibility to Radiation

The radiation environment in which the exciter-regulator will be placed was specified for this preliminary design only and not for the previous portions of the study. The specified radiation level may possibly be too severe for the silicon semiconductors, especially the controlled rectifiers, which are required in this design. Therefore, additional study is recommended in this area to determine the actual effect of the specified radiation upon the present design and to determine what shielding, if any, is necessary to sufficiently protect the present design.

2. Radio Interference

No requirements concerning radio interference characteristics have been defined for this study program, and so radio noise suppression filters have not been included in the design. However, the use of high-current silicon diodes and controlled rectifiers, operating at 1000 cps, may produce considerable high frequency radio noise. Depending upon the degree of suppression required, if any, suppression techniques may become quite involved and additional study in this area may be required.

3. System Voltage Buildup

No consideration has been given to the method of building up the system bus to rated voltage. Either system residual voltage or a d-c power supply external to the system may be used to provide buildup excitation. In either case additional switching circuits will be required. When the system is more specifically defined an investigation should be undertaken to determine the most appropriate method for system voltage buildup.

4. Parallel Operation

Provisions have been included in the preliminary design for dividing real load at the d-c bus. The load division circuit was included as a conceptual design only. No consideration was given to the design of the load sensing current transformer required to supply the load signal to the load division circuit. Furthermore, no consideration was given to the detailed design of the load division circuit, especially the sensitivity which may be required. When the system parameters are better defined, particularly the turbine drive and control characteristics, further study is recommended to determine the real load division characteristics of a four unit paralleled system. Such a study should determine the sensitivity required for the load division circuit.

A. ELECTRICAL DESIGN

1. Power transformer

The power transformer design was selected from a number of designs to provide minimum system weight. The selection was based on a cooling system weight penalty of 12.5 pounds per kilowatt of loss. The losses were based on a temperature of 850F as it was estimated there would be a 300F temperature gradient between the cooling fluid and the copper and iron.

In the transformer design, a number of assumptions were made as a basis for the design. It was assumed the copper had 100 percent conductivity at the temperature at which the losses were calculated. It was assumed the temperature effect on the iron would be the same for frequencies above 400 cps as it is for frequencies below 400 cps. Available 400 cps data was then projected to give working values. It was also assumed that a tape wound core using an inorganic binder would be used because of cooling efficiency. Inorganic binders for tape wound cores to temperatures of 1100F are under development at the present time and appear to be feasible. An alternate material for the core would be "Cubex", but used in punching form which adds about 6 percent to the core weight.

The transformer parameters for 100 percent load are:

Input	339 KVA		
Output	330 KVA		
Copper Weight	30 Pounds		
Iron Weight	49.8 Pounds		
Total Weight (Electro-Magnetic)	79.8 Pounds		
Losses, watts	1 p.u.	.75 p.u.	.50 p.u.
Copper	4000	2500	1000
Iron	2200	2200	2200
Total	6200	4700	3200

2. Current Transformer

The current transformer design was made with the same basic assumptions as the power transformer. The construction, although on a smaller scale, is the same as the power transformer. However, the current transformer differs in the basic design because the rating of the current transformer is determined by the generator excitation required at three-per-unit fault current.

B. TRANSFORMER MECHANICAL DESIGN

The power transformer and the auxiliary current transformer are mounted in a single package. Preliminary design data are presented in Table 17.

TABLE 17.

Mechanical Design Data

Weight (lbs.)	
Power Transformer Electro-Magnetic	79.8
Current Transformer Electro-Magnetic	4.9
Total Electro-Magnetic	84.7
Transformer Dry Weight	143.8
Transformer Wet Weight	145.3
Losses (Watts)	
Power Transformer	6200
Current Transformer	40
Total	6240
Coolant	
Flow, lbs/min.	20
Pressure drop, psi	0.012
Inlet Temperature	450
Outlet Temperature	550
Outline Drawing	Figure 54

Steel support beams are clamped along the open edges of the power transformer core and extend beyond the coils directly to mount points. At one end of the power transformer the auxiliary current transformer is similarly mounted on crossbeams between the power transformer structural supports. Coolant ducts are supported by brackets from the beams. Core forms provide insulation and support for the coils on the core legs. Additional support to the coils is given by support straps and brackets, impregnant and potting, and, in the case of the power transformer, coolant ducts.

Coolant fluid is ducted over the core and through the coils of the power transformer to reduce the internal temperature drop. A tape-wound core is clamped between cold-plates which cover the surfaces formed by tape edges. Coolant ducts are welded or brazed to the plates along the legs beneath the coils. Ducts and cold-plates are of columbium-zirconium alloy. Similar ducts are passed between the primary and secondary windings at each end of each coil, perpendicular to the direction of winding. All ducts and plates are electrically insulated from the windings.

TRANSFORMER OUTLINE DRAWING

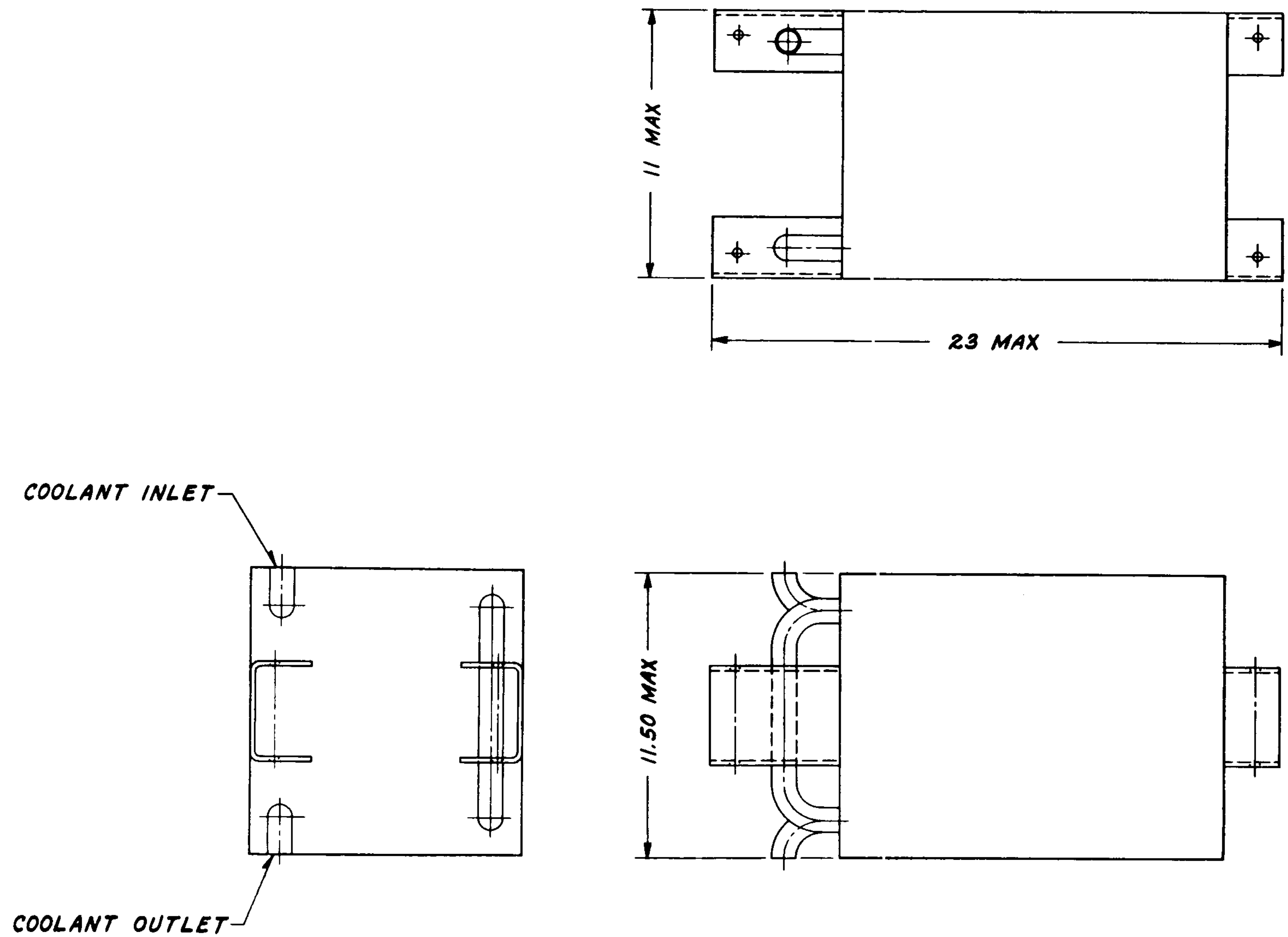


FIGURE 54.

XI POWER-RECTIFIER PRELIMINARY DESIGN

Power transformer core losses are assumed to be conducted through the core iron impregnant and cold-plate to the coolant ducts. Copper losses are assumed to be conducted through the layers of copper, insulation, impregnant, and potting to the coolant ducts laminar flow liquid convection then cools the duct walls.

The auxiliary current transformer core is clamped between cold plates in the same manner as the power transformer with coolant ducts joined to the plates along the core edges outside of the coils. Due to the relatively low losses in this transformer, coolant ducts within and beneath the coils are unnecessary. The unit is potted to facilitate heat conduction from the coils to the coolant ducts.

C. LIST OF MATERIALS

a.	Coolant	Liquid Potassium
b.	Coolant Tubes	Columbium-zirconium Alloy
c.	Heat Sink	Copper
d.	Supporting Structure	High strength austenitic steel or a stable stainless steel (Type 321)
e.	Hardware	High strength austenitic steel or a stable stainless steel (321)
f.	Cooling Tube Insulation	Mica
g.	Conductor	Copper
h.	Core	Silicon Steel
i.	Insulation	Mica, glass, asbestos, and combinations of the preceding

A. ELECTRICAL DESIGN

This preliminary design is based on the following electrical requirements.

Output Power:	250 kw
Output Voltage:	5000 volts d-c
Input Frequency:	1000 cps
Phases:	3

The rectification method chosen is the silicon-diode, full-wave-bridge circuit described in Section III-A of volume 2. This design uses 17 silicon diodes in series for each of the six legs in the rectifier bridge. Each diode is electrically shunted with a resistor and capacitor. Table 18 lists the components selected for this preliminary design.

There has been no filtering of the d-c output voltage included in this design. It is estimated that the rms ripple voltage will be 5 percent of the d-c output voltage for resistive loads.

Figure 55 is a calculated performance curve of the rectifier assembly through the maximum rating of the rectifier components. This curve shows conversion efficiency as a function of output power at rated input and output voltage. These efficiency calculations are based on the assumption that the input voltage source has zero internal impedance. A final design calculation of efficiency would require that the source impedance be known and considered in the calculation. The subtransient reactance of solid rotor generators has a significant effect on conversion efficiency and voltage regulation as section VII shows. It is recommended that this area be given careful consideration in a final system design.

No consideration has been given to the elimination of radio frequency interference frequently encountered with silicon rectifier circuits. Allowable limits should be specified for a final design and filtering should be provided if necessary. This filtering is not expected to be a problem but will slightly increase the size and weight and decrease the overall efficiency of the rectifier assembly.

The tolerance of this preliminary design for the radiation environment specified has not been determined. Materials used in this assembly have been specified for this determination and should be considered during a final design. It is expected that some shielding or changes in material will be required for prolonged operation in this environment.

TABLE 18.

Rectifier Electrical Data for 250-KW, Silicon-Diode Rectifier

D-C Bus Volts		5000
Diode	Type	JEDEC 1N1190, 800 PIV
	Number Required	102
	Loss, Watts/Diode	20.1 at F. L.
	Weight, pound/Diode	0.058
Resistor	Type	Metal Cased, Wire Wound 40K Ohms
	Number Required	102
	Loss, Watts/Resistor	0.97
	Weight, Pounds/Resistor	0.0165
	Size, L x Dia., Inches	1.44 x 0.385
Capacitor	Type	0.01 uf at 600 WV, d-c
	Number Required	102
	Loss, Watts/Cap.	0.023
	Weight, Pounds/Cap.	0.013
	Size, L x Dia., inches	1.125 x 0.562
Conductors	Type	Copper, 10 AWG
	Loss, Watts	17 at F. L.
	Weight, Pounds	0.7
Total Loss, Watts		2168
Conversion Efficiency		99.1

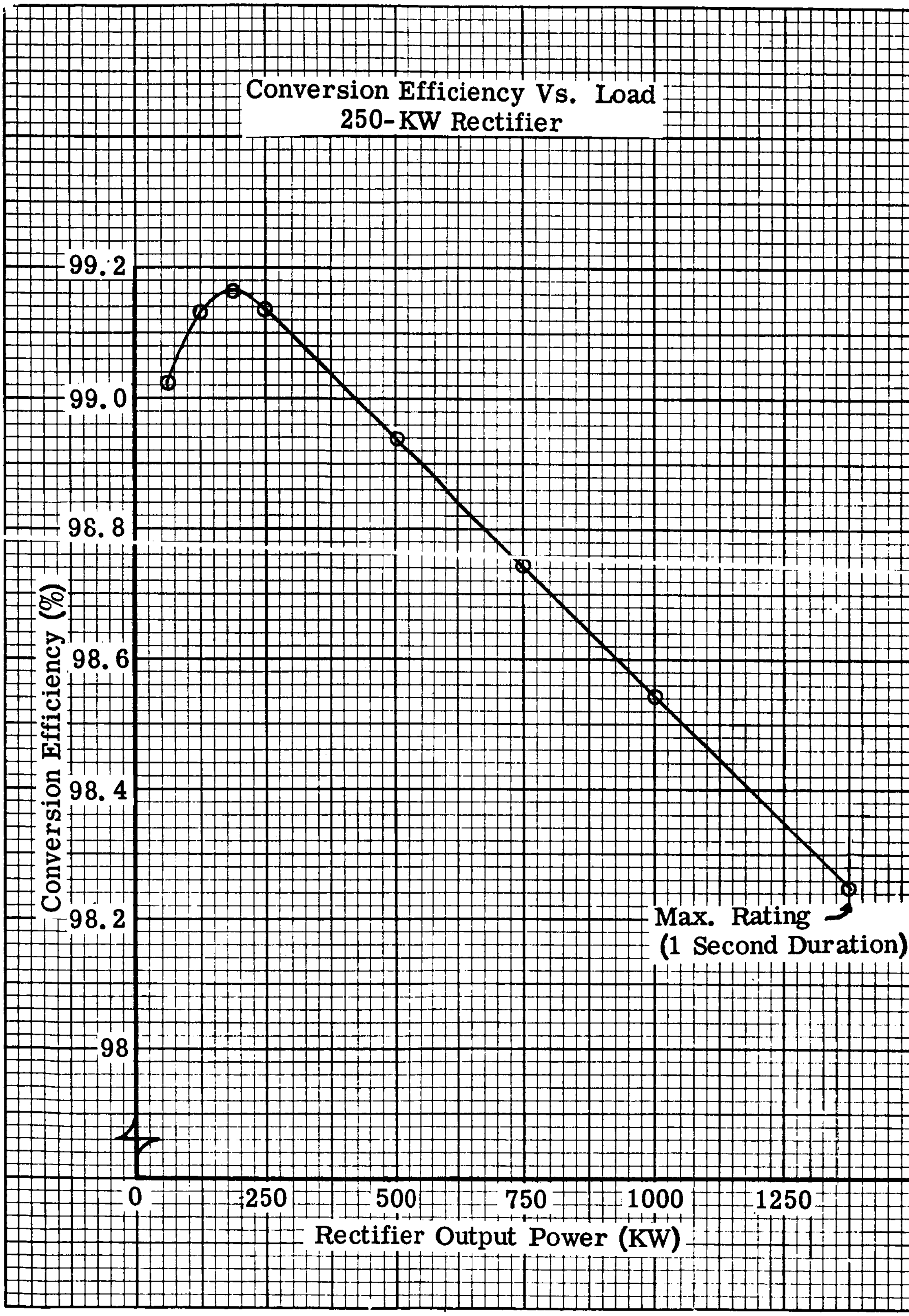

Conversion Efficiency Vs. Load
250-KW Rectifier
99.2
99.0
98.8
98.6
98.4
98.2
98
Conversion Efficiency (%)
Max. Rating
(1 Second Duration)
0
250
500
750
1000
1250
Rectifier Output Power (KW)

Figure 55.

B. MECHANICAL DESIGN

Preliminary design data for the 250-kw rectification system is presented in Table 19.

TABLE 19.

Dry Weight	33.9 lbs.
Wet Weight	35.8 lbs.
Coolant	Monisopropyl Biphenyl (MIPB)
Coolant Flow	30.0 lbs./minute
Coolant Inlet Temp.	165F
Coolant/Outlet Temp.	175F
Coolant Pressure Drop	0.85 psi
Heat Load	2170 watts
Outline Dwg. No.	Figure 56

Each diode is mounted directly to a beryllium oxide insulation plate with a resistor capacitor clip mounted to the plate adjacent to the diode. Insulation plates, in turn, are adhesive bonded to an aluminum cold plate with mechanical fasteners to insure positive support. Adhesive bonding allows direct conduction of heat from the insulation to the cold-plate, eliminating the thermal resistance inherent in an air gap. The low elastic modulus of adhesive bonding agents, plus expansion gaps left between the insulation plates, serves to avoid high thermal stresses caused by differential expansion between the insulation and the aluminum cold-plate. The cold-plate is formed aluminum sheet, with coolant tubes or ducts brazed or welded to the underside of the plates.

Electrical components are cooled by conduction of heat through the insulation to the cold-plate, with turbulent flow liquid convection used to maintain cold-plate temperature. Monoisopropyl biphenyl was chosen as the coolant. For its properties, refer to section II of Volume 1.

Diode junction temperatures are limited to 288F (142C) derated 25 percent from the maximum junction temperature of 190C specified by the manufacturer. Beryllium oxide insulation is used to obtain low thermal resistance with electrical insulating properties. Overall thermal resistance between the rectifier case and the cold-plate is assumed to be 2.09F/watt.

Diodes are arranged in six rows of eight and nine diodes, alternating on each of two decks. Thus, each leg of 17 diodes is contained in two rows. Each row is cooled by one duct carrying 15 pounds per minute of coolant, with the ducts on each deck joined in series. The coolant flow of 30 pounds per minute is divided between the two decks.

XII CIRCUIT BREAKER PRELIMINARY DESIGN

RECTIFIER OUTLINE DRAWING

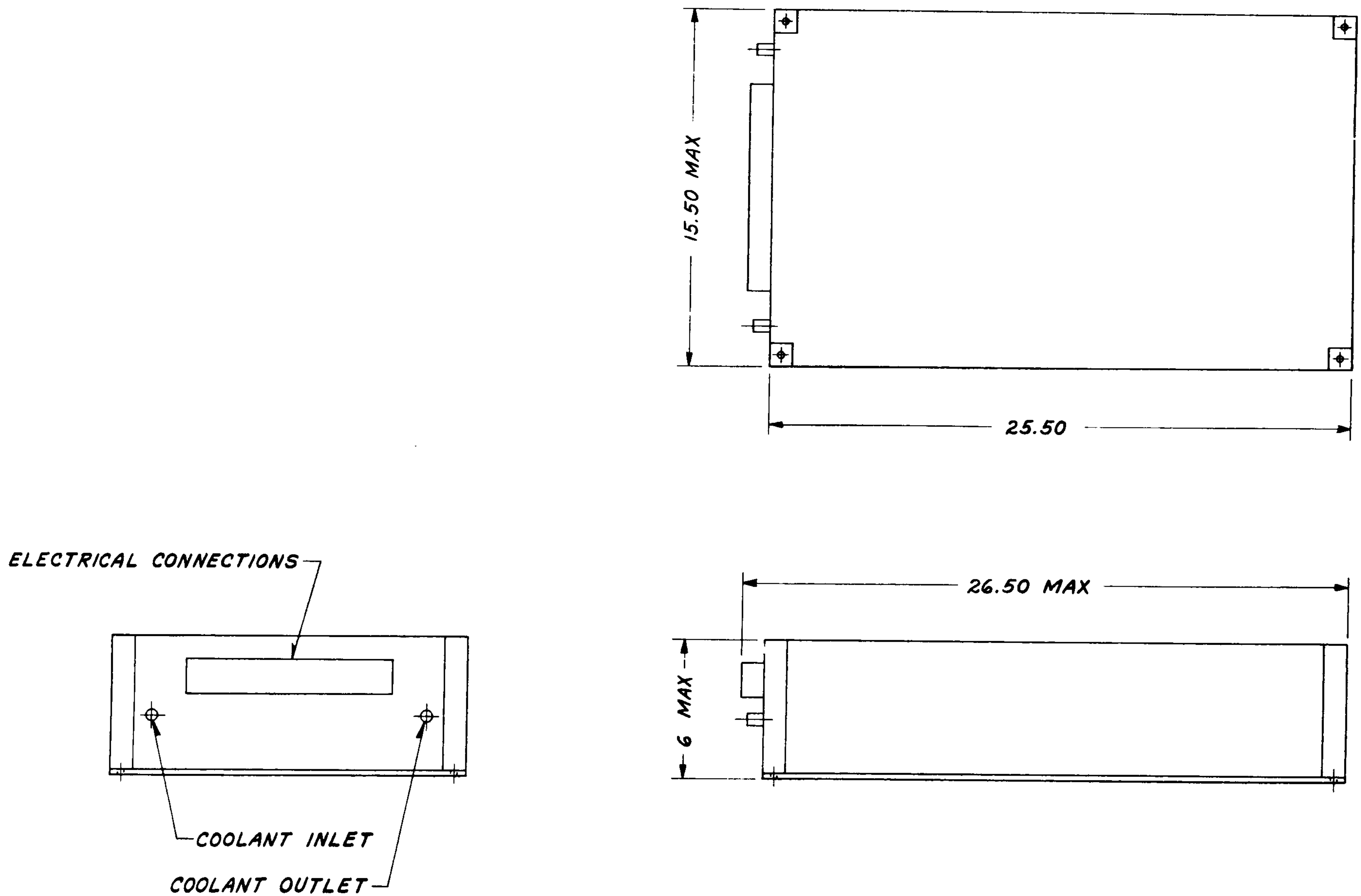


FIGURE 56.

C. LIST OF MATERIALS

The following materials are used in the rectifier assembly described:

Diodes	Silicon alloy, nickel plated copper case, glass hermetic seal, hard solder connections, nickel plated copper anode terminal.
Capacitors	Bendix E-200 Series, reconstituted mica insulation, aluminum foil, glass hermetic seal.
Resistors	Wire wound, metal cased, tinned copper leads.
Hardware	Carbon steel QQ-S-633, FS1010, Nickel Plate.
Mounting Clips	Nickel Plated Steel.
Solder	Tin 60%, lead 40%.
Insulation	Beryllium Oxide.
Structure & Tubing	Aluminum QQ-A-318 Cond. 1/2 hard.
Conductors	Copper

A. ELECTRO-MECHANICAL DESIGN

1. Design Data

The design of the line circuit breaker was based on the fundamental considerations developed in the parametric study (Section VI). Briefly restated, these are:

a. The circuit breaker is a 3-pole, single-throw (3PST), latch-type, remotely operated device.

b. The unit is of non-sealed design to utilize the superior dielectric properties of the space vacuum.

c. The contact materials selected are copper-columbium as determined by mutual insolubility considerations.

Table 20 summarizes the electrical and mechanical data for the circuit breaker.

TABLE 20.

Design Data For Circuit Breaker

Dry Weight, pounds	6.5
Wet Weight, pounds	6.8
Coolant	Potassium
Flow, lbs/min.	1.4
Pressure drop, psi	0.002
Inlet Temperature	495F
Outlet Temperature	505F
Losses (watts)	
0.5 p.u. load	9
0.75 p.u. load	20
1 p.u. load	36
2 p.u. load	144
4 p.u. load	578
Outline Drawing	Figure 57

2. Configuration

The selection of the power circuit configuration was based on eliminating all sliding or rolling surfaces in the breaker. Power is brought into the unit through a copper feed-through insulated with beryllium oxide. (Beryllium oxide is used to provide the necessary insulation and to provide a good thermal path to the structure.) Molybdenum flexible straps are

CIRCUIT-BREAKER OUTLINE DRAWING

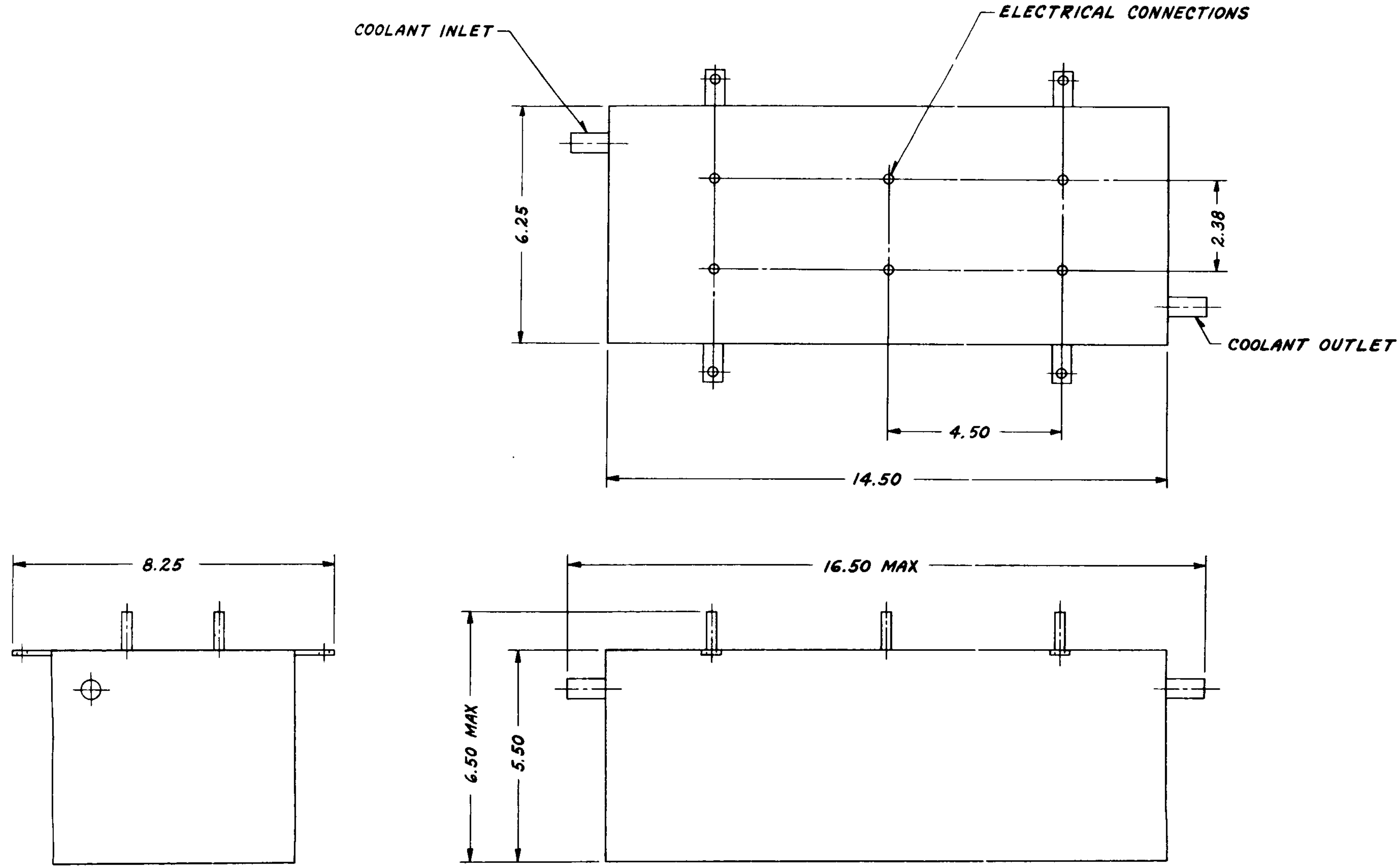


FIGURE 57.

mounted on the feed-through extension with the copper movable contact mounted on the opposite end of the straps. (Molybdenum was chosen as a compromise between electrical resistivity and mechanical strength needed for the flexing straps.) A columbium stationary contact is mounted by means of beryllium oxide insulation in line with the copper movable contact. A vapor shield is mounted around and concentric to the stationary contact. Columbium is used for the other feed-through as a common member with the stationary contact.

3. Actuating Mechanism

A plate type armature magnet and a permanent magnet latch are located between phases. A cross arm is provided which is mechanically coupled to the movable contact of each phase by electrically insulated springs. These springs provide contact overtravel forces. The cross arm is actuated by the close magnet and the latch by means of magnetic coupling which counteracts the permanent magnet holding force.

4. Cooling

Electrical heat losses are conducted through contacts, molybdenum support straps, feed-throughs, and insulation to the unit base. The base is cooled by laminar-flow liquid convection through a coolant conduit joined to the base. The base and coolant conduit are of columbium-zirconium alloy to facilitate compatibility with liquid potassium coolant. Additional structure is of stainless steel. Contact temperature is limited to 675F at 1-per-unit load.

In an actual system design, the above losses listed above might just as effectively be dissipated by radiation to an external sink, as pointed out in the parametric study. However, for the purposes of this study, it was decided to design the circuit breaker as an independent unit and not rely on an unspecified heat sink.

B. LIST OF MATERIALS

The following materials would be used in the circuit breakers described above:

Contacts	Copper and Columbium
Contact Supports	Copper
Contact Arm	Molybdenum
Insulation	Beryllium Oxide
Base and Cooling Tubes	Columbium-Zirconium Alloy
Structure and Cover	Type 321 Stainless
Hardware	Type 321 Stainless and possibly a high strength austenitic alloy (such as Discaloy or A-286)
Solenoid	Armco Iron, copper, Alnico 5
Spring	Inconel x or Rene' 41

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